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FOR PROMOTING USEFUL KNOWLEDGE

79 April 21, 1938 No. 1

GEOPHYSICAL EXPLORATION OF THE OCEAN BOTTOM

SYMPOSIUM ARRANGED BY
THE AMERICAN GEOPHYSICAL UNION

HELD AT

THE AMERICAN PHILOSOPHICAL SOCIETY
November 26, 1937

PHILADELPHIA
THE AMERICAN PHILOSOPHICAL SOCIETY
Independence Square
1938

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American Philosophical

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FOR PROMOTING USEFUL KNOWLEDGE

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THE IMPORTANCE OF GEOPHYSICS TO SUBMARINE GEOLOGY

RICHARD M FIELD

Chairman, Committee on Geophysical and Geological
Study of Ocean Basins A G G U

Because of the magnitude of the subject and the large number of papers, for the time allowed, each speaker can hardly hope to do more than outline the essential matter within his potential field I shall, therefore, make my remarks as brief as possible, with no desire to "beg the argument" or to present conclusions previous to the evidence from which they may be properly deduced

Submarine geology, or the exploration of the submarine and suboceanic lithosphere, is not properly a subdivision of oceanography, except in so far as it makes use of the experience of individuals and the equipment of institutions engaged in the physical, chemical, and biological study of marine and oceanic waters Submarine geology differs only from terrestrial geology by the methods employed in mapping and sampling a major portion of the surface of the earth which is covered with water, from a few feet to several miles in depth Until quite recently, the geologist has had neither the opportunity nor the machinery for exploring the topography, sedimentation, lithology, and structure of the suboceanic lithosphere In fact, he was worse off than the astronomer who, even if he can not collect specimens of the moon, can at least photograph and map the major features of a complete sample (one-half) of its entire surface This inability to acquire even fundamental physiographic data for the great suboceanic areas has unquestionably led geologists to consider them relatively negligible or *negative* as compared with the continents, whose stratigraphical and structural evolution is becoming increasingly well known. This *influence of ignorance* is clearly expressed in such opposed major geological hypotheses as "the permanency of ocean basins" and "continental drift," both of which, however, include the postulate that the ocean basins never were dry land. This postulate of the permanency of ocean basins is all the more intriguing, for, since the suboceanic lithosphere must have been affected by deformative processes, topographic maps of significant areas will allow the geologist to study the contours of strongly pronounced folds and scarps which, as they developed, have not been subjected to erosion On the other hand, if such a significant area as the middle Atlantic ridge is proved to have a distinctly subaerial topography, such information will tend to weaken the postulate of the permanency of the Atlantic ocean basin For several reasons, it would be interesting to compare and contrast the physiographies of the Subatlantic and Subpacific lithosphere To put it still more plainly, any accurate topographic data regarding the sub-ocean lithosphere are bound to be of great geologic importance

It is interesting to note that the theory of isostasy is particularly significant for two reasons First, because of geological and geophysical evidence as to the structural evolution of continents, and, second, because of geophysical data concerning both continents and ocean basins Thus a peculiar importance of the theory of isostasy is that it is the outstanding attempt to explain the origin and evolution of the major structural features of the lithosphere in terms of coordinated geological and geophysical data Many geologists have quite properly claimed that many of the structural features of continents, especially great folds and overthrusts can not be either directly or indirectly due to isostasy, and, therefore, it is not an all-inclusive factor or complete *modus operandi* for explaining diastrophism, including the origin of mountains On the other hand, the support obtained for isostasy by the coördination of gravity data and geological observations has quite recently spurred a few geologists to include gravimetric and other geophysical techniques in their surveys for fundamental structures, both continental and suboceanic, with remarkably interesting results

The keynote of this symposium on suboceanic geology is geophysics. This is true for two reasons First, because geophysical methods are the best for mapping the topography of the ocean bottom, and, second, because only geophysical methods may be employed to determine the composition and structure of the suboceanic lithosphere What, therefore, is geophysics?[1] According to Dr G Angenheister, Director of the Geophysical Institute of the University of Gottingen, the word "geophysik" appeared in Meyer's *Conversatsionslexicon*, published in 1853 The term must have been in use sometime before that. Both A Muhry (1863) and K Loppritz, Sr., aided in procuring its general acceptance Among the first comprehensive treatises in the English language on the subject is *The Physics of the Crust*, by G Osmund Fisher, published in 1861 The scope of geophysics is broad and difficult to define, especially in relation to geology. It is important to note that geophysics is not necessarily synonymous with physical chemistry, and, therefore, with geochemistry, although both are intimately related to geology In the field of geophysics, the many methods and techniques are classified as either acoustic, gravimetric, seismic, magnetic, electric, geothermal, or radioactive All of these methods have been applied to the study of the structure of continents More recently several of these methods have been applied to the study of the suboceanic crust of the earth, and all of them may soon be as effectively and accurately controlled from a ship or from a submarine as they now are from the dry and stable platform of the land

During recent years geophysical techniques have been highly developed, particularly in relation to prospecting for petroleum through the mapping of subsurface geological structures, the traces of which may, or may not, be exposed at the surface of the earth. With the possible exception of atomic and astronomical physics and certain phases of meteorology, the greatest field of geophysics has been the development of classical physics as applied to problems in geodesy and structural geology, both fundamental and economic. Today, geophysics bridges the gap between physics and geology. Thus geophysics is not a "borderline science" because its methods and derived data are properly interpreted only in terms of structural geology Geophysical methods, therefore, are among the many, including those of geochemistry, paleontology, mineralogy, petrology, etc , which are available to the geologist in his study of earth processes and earth history

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[1] Geophysics Encyclopedia of Science, Van Nostrand, 1938

The geologist has discovered that the history of the earth is expressed not only in the present irregularities of its surface, but also in the rocks out of which the present surface has been carved by the several processes of erosion While many of these rocks were originally formed at or near the surface of the earth, some of them show evidence of having been subsequently buried to a depth of ten to twelve miles before they were again exposed at the surface Thus the geologist is reasonably sure that he has available at the surface of the earth samples of practically all types of rocks which have been formed throughout the *geological* history of the earth This great history of the conflict between processes of diastrophism, its accompanying vulcanism, and the processes of denudation is written in terms of structural geology, as disclosed by the arts of the stratigrapher and structural geologist The geologist and geophysicist in their studies of continents have discovered that by working together they can extend both the depth and area of their structural survey of the crust of the earth, and thus greatly add to our knowledge of its history

Thus the increasing success of geophysical methods is largely, if not entirely, due to the mutual education and close cooperation of geologists and geophysicists The primary responsibility of the geologists has been to determine the areas to be surveyed and the manner of their surveying, and to help the geophysicists interpret their data in terms not only of petrology but rather of structural geology The duty of the geophysicists has been to adapt and develop the application of experimental physics to the geophysical exploration of the earth's crust, and to suggest to the structural geologist new methods and techniques for extending the area as well as the depth of his surveys During the development of this geophysical-geological cooperation, there naturally and properly arises, from time to time, considerable debate as to the relative values of the purely geophysical and purely geological data This debate has not only greatly advanced our knowledge of the structural geology of continents, but has also expanded the field of geophysics

In considering the exploration of the suboceanic crust, we must take into account the special features of the problem First, in terms of the relatively small amount of available physiographical and geological data concerning the suboceanic as compared with the continental crust second, in terms of existing geological hypotheses and theories advanced to explain the origin of continents and ocean basins, and, third, in reference to the present and future possibilities of geophysical methods of obtaining accurate data concerning the physiography and structure of the 70 to 80 per cent of the crust of the earth which is covered by water and ice The outstanding geological problem is the permanency of oceanic basins, and it is doubtful if this problem can be solved by the study of the continents and oceanic islands alone

Many, if not most, of the major continental structures border the continents, and most continental structures certainly continue beyond the strand line, perhaps even beyond the continental margin For example, we now know that the structure of the Appalachians not only suggests that the thrusting came from the oceanic area, but also that we can see only the western side of what was probably a more symmetrical and widespread orogeny which was not terminated at the continental margin unless it has been torn away from complementary, transatlantic structures This suggestion, affected as it is by the lessons learned from the long study of the Alpine and Scottish-Scandinavian geosynclines, is diametrically opposed to the earlier and simpler concept of the origin of the Appalachian geosyncline and its associated geanticline, Appalachia Regardless of any, or all, geological theories concerning the origin of ocean basins, we should attempt to trace known continental structures across the submerged continental margins and into the suboceanic lithosphere. This is particularly true for the Atlantic Ocean basin, the stratigraphic and structural matching of whose continental margins has been the chief stimulus to the several hypotheses which attempt to explain the major pattern of the face of the earth. What we particularly need are physiographic and structural data concerning the Atlantic, Pacific, Indian, and Arctic suboceanic crust Can geophysical methods help us to acquire these data First, by penetrating the oceanic waters which cover more than two-thirds of the surface of the earth, second, by providing accurate topographic maps of the suboceanic crust, third, by providing us with samples of the sediments wherever they may occur on the surface of the topography, and, fourth, and most important of all, help us to carry our structural studies deep beneath the ocean bottom, with the same degree of accuracy which is now obtained in the geophysical-structural exploration of the continents. This question is the primary object of this symposium and the following roundtable conference

In closing, I should like to call to your attention a phase of the geophysical exploration of the ocean bottom which is of considerable political and human interest, namely, that the major portion of the earth's crust constitutes a vast "no man's land," as yet practically unexplored and either policed or fought over by hundreds of naval vessels which plow the waves from one to several miles above its surface. Many of these naval vessels, including submarines and mine sweepers, are admirably adapted to the geophysical exploration of the suboceanic lithosphere Indeed, without such naval assistance, we can not hope to execute a detailed and comprehensive survey of even a significant portion of the suboceanic lithosphere with reasonable economy and efficiency Following the precedent which has already been set up by the individual efforts of the Dutch, British, German, French, Italian, and American navies in relation to sonic gravitational and magnetic surveys, is this not an excellent time to suggest that the complete geophysical exploration of the ocean bottom is of common scientific interest to all nations even if they never can hope to take possession of it, any more than the astronomers are able to colonize the planets or their satellites

NEW METHODS OF MARINE SURVEYING

CAPTAIN G T RUDÉ

Chief, Division of Hydrography and Topography
U S Coast and Geodetic Survey

It gives me pleasure to accept the invitation of your society to describe briefly the methods used for the offshore hydrographic surveys which the Coast and Geodetic Survey has been making in recent years The officers of the Coast and Geodetic Survey rightly consider the hydrographic surveys conducted for making nautical charts as the routine and immediately practical work of the Bureau and regard the nautical charts themselves as paramount to the safety of life and property at sea It is fortunate, however, that these surveys, required for a utilitarian purpose, do have scientific value in themselves in addition to the contributions which come from the development and use of scientific methods in the work, which from time to time bring unexpected additions to scientific knowledge The areas dealt with embrace in general the continental platforms, submerged mountains, and submarine valleys Although the regions include only a small portion of the great ocean basins, they do represent a relatively large share of the oceanographic problems

The deep ocean basins now appear to have had a similar geologic history to the surfaces of the continents above the sea The beginning of the period of enlightenment, I believe, can be attributed to the application of sonic methods to hydrographic surveys The development of echo sounding, for instance, has been not only a great aid to navigation, but it has in turn made it possible to survey many hundreds of square miles in less time than required to take a few scattered deep soundings by old methods in use when I joined the Survey thirty-five years ago The other important factor is the development of radio acoustic ranging for controlling hydrographic surveys well out to sea

At sea beyond the range of visual positions which can be obtained from sextant angles on shore triangulation stations, positions of the survey ship have heretofore been subject to considerable uncertainty, this uncertainty naturally increasing with the distance beyond the limits of the shore control. Various methods were attempted and utilized for controlling hydrographic surveys out of sight of land, but none of these gave satisfactory accuracy of position until radio acoustic ranging was developed Soundings made by wire and sinker are quite accurate as to depth when taken under good conditions of weather and sea, but the uncertainty of the actual offshore positions until recent years often led to erroneous deductions from the soundings For example, the few soundings made in the vicinity of the Hudson Submarine Valley prior to the work of the past year (1936) indicated an S-shaped outer valley This was due in part to the inaccuracies of position in some of the earlier soundings and also to the scarcity of soundings in the region The work of 1936 has proved that the few deep soundings from which the erroneous inference was made were taken in an entirely different submarine valley to the northeast of the main Hudson valley Many other examples could be cited

Echo sounding instruments now have been developed to such a degree that practically a continuous accurate profile of the sea bottom under the surveying vessel's course can be obtained The number of soundings to be recorded depends almost wholly upon the facility with which they may be written down in the record Some forms of echo sounding instruments actually record the profile of the vessel's course on a graph. It is interesting to contrast this modern ease of sounding with that of the Challenger Expedition, which on the notable cruise between the years of 1873 and 1876 made a total of 504 deep-sea soundings, or with the record of the *Blake* between 1874 and 1879 when the then remarkable number of 3,195 deep-sea soundings was achieved. Now in contrast, in fifteen working days in the month of July 1937, the party on the Coast and Geodetic Survey Ship *Lydonia* recorded 12,498 soundings on the continental slope and covered an area of 1,764 square statute miles extending more than 150 miles offshore, all of which was precisely controlled by radio acoustic ranging and taut wire traverses tied in to the shore triangulation net on North American 1927 Datum. This included the time required for two trips to port for supplies

During five months in the summer of 1937 the party on the Coast and Geodetic Survey Ship *Hydrographer* covered an area in the Gulf of Mexico of 6,513 square miles off the Texas coast, recording 82,986 soundings

Similar results have been accomplished on the Pacific coasts of the United States and Alaska Within the past six years, 285,000 square statute miles of marine surveys have been made of the coastal waters of the United States and possessions. This is no inconsiderable portion of the earth's surface While the greatest contribution to science represented by these surveys probably is the physiographic detail mapped in the course of the surveys, there are other results valuable to science Bottom specimens have been taken and temperature and salinity observations have been made. The determination of the characteristics of the ray paths of sound waves in sea water, resulting from the experiments made in the Santa Barbara Basin off the coast of Southern California in 1935 and 1936 by the Coast and Geodetic Survey Ship *Pioneer*, is a contribution of fundamental importance These experiments were made primarily to establish the soundness of our ray-path theories for further increasing the accuracy of radio acoustic ranging and to learn something of the anomalies to be encountered in practical sonic work utilizing the velocity of sound in sea water Briefly, the results of these experiments confirmed the relation between the apparent horizontal velocity of sound and the theoretical velocity corrected for bottom temperatures and salinities in shoal water. This relation has been known for some time, and although empirical it has provided a very convenient method for use in practical radio-acoustic ranging It was definitely established that the sound travels in a series of reflections and refractions, with some diffraction for short distances, and that the path is materially affected by the even or uneven character of the bottom or steep slopes near the receiving hydrophone.

It was found that the apparent horizontal velocity of sound in the open sea is a discontinuous function of the distance, the magnitude of the discontinuities depending on the bottom profile, depth and size of the bombs, and sensitivity of the hydrophone With decreasing depth of bottom, or increasing bomb-size, the magnitude of the discontinuities decreases and may become negligible under certain conditions Many other interesting and valuable facts were disclosed by these experiments, a study of which is now being made and which it is believed will materially add to the accuracy and efficiency of radio-acoustic ranging methods The British Admiralty Tables of theoretical velocities of sound in water were verified within two-tenths of one per cent With these valuable tables confirmed by actual comprehensive tests, one can see that the velocity of sound anywhere in the ocean may be obtained by temperature and salinity observations, and this makes easily available a length or base for any desired explorations of limited areas at sea

Another important contribution comes from the discovery of numerous submarine valleys indenting the edges of the continental shelves and the establishment of the apparent stream-erosion nature of the valleys A few of the more prominent ones are illustrated in the accompanying figures. The discovery of well dissected submarine regions indicates the desirability of further exploration of some of these features in other parts of the earth by the methods now at our disposal

A better conception of the nature of these surveys and the practicability of application to studies of the ocean basins can be had when the methods are understood Echo sounding is almost self-explanatory A description of the development of the various forms of commercial instruments for this purpose is hardly necessary. The instruments so far used by the Survey have been commercial forms of the Fathometer, slightly modified by our own engineers to increase the accuracy, except the Dorsey Fathometers which were developed in our laboratory Essentially the Fathometer indicates depths by measuring the time required for a sound impulse to travel to the sea bottom and for the echo to return This usually is done by a flashing light on a rotating disc behind a

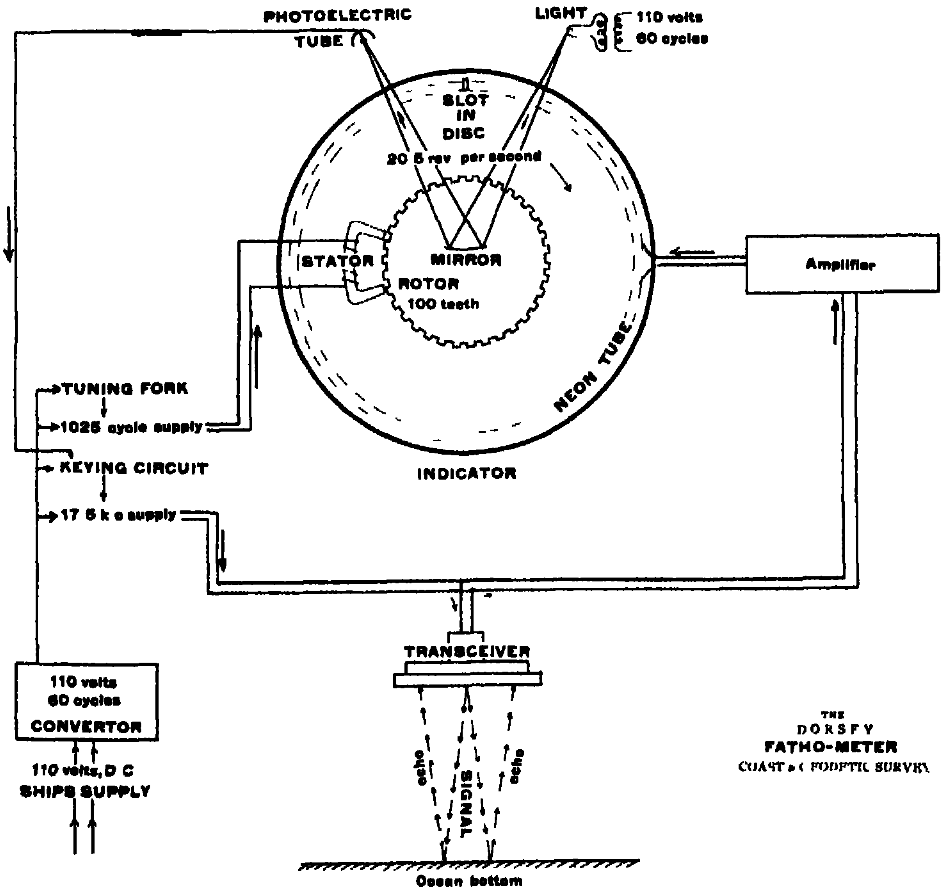

FIG 1 Schematic representation of Dorsey Fathometer No 1

graduated dial. The accuracy of the instrument depends upon the constancy of speed of rotation of the disc, and to insure the accuracy desired, a synchronous motor controlled

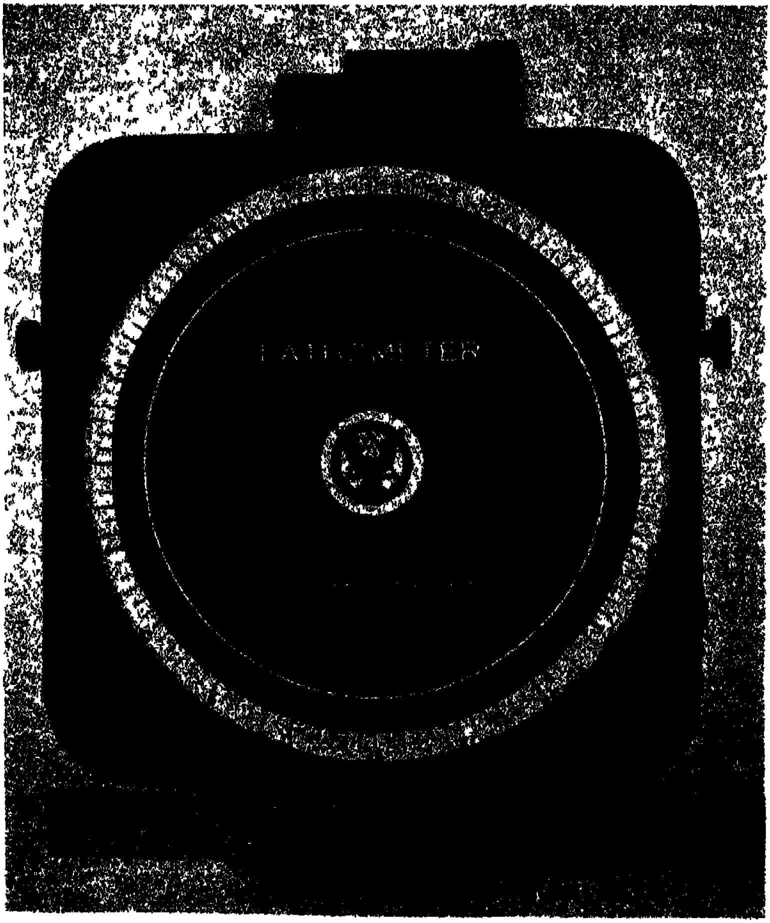

FIG 2 Dorsey Fathometer No 1, front view

by a tuning fork is used in the Dorsey Fathometers. The sketch in figure 1 illustrates the general arrangement and operation of the Fathometer and figure 2 shows the appearance of the indicator.

The method of radio acoustic ranging (called R A R for brevity) has given a satisfactory and accurate means for position determination at long distances from shore It is illustrated graphically in figure 3 Two or more radio stations on shore are automatically keyed by subaqueous impulses received by the hydrophones anchored at some distance from shore The surveying vessel, using small bombs of TNT, proceeds along the necessary courses sounding with fathometer When a position is necessary a bomb is dropped overboard The time of explosion is recorded on a chronograph tape on the ship The sound travels through the water and when the impulse reaches the hydrophones inshore, radio impulses are sent to the surveying vessel and recorded upon the same chronograph tape as was the original explosion The time interval thus measured, multiplied by the apparent horizontal velocity of sound in the water gives the distances of the surveying ship from the several hydrophones The positions of the hydrophones are always determined with reference to the triangulation on shore On the Atlantic and Gulf coastal shelves it has been necessary to place the hydrophones well out from shore in order to avoid the serious attenuation of the sound experienced in very shoal water For this purpose it has been the practice, until the last year, to use station vessels The development of the sono-radio buoy has been successful and figure 4 illustrates the method of R.A R with sono-radio buoys replacing the station ships The sono-radio buoys have been used up to sixty miles or more.

The taut wire apparatus is a device developed by the British. It is a large reel of fine wire (usually over 140 nautical miles) which can be payed out under uniform tension over a registering wheel or sheave as the surveying vessel steams along, thus enabling the surveyors to measure distances accurately in water of relatively shoal depths and over uniform bottom.

The sketch in figure 5 illustrates the correlation of the various methods used in making a survey over such an

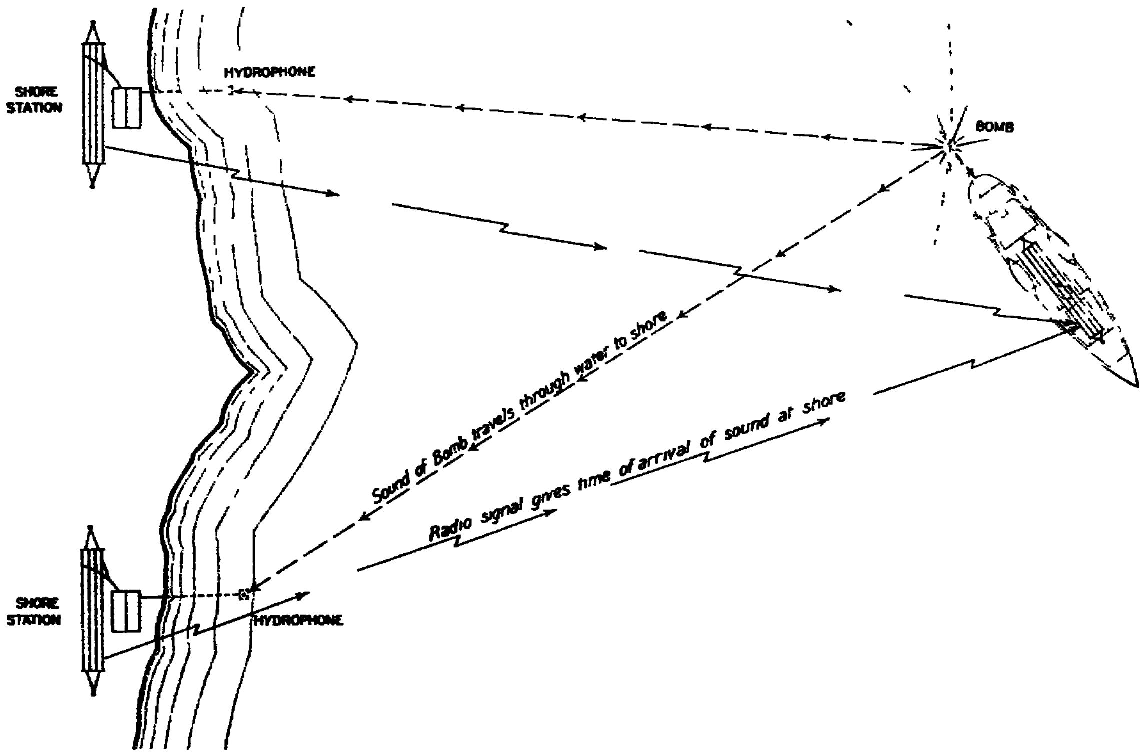
SHORE STATION
HYDROPHONE
BOMB
Sound of Bomb travels through water to shore
Radio signal gives time of arrival of sound at shore
SHORE STATION
HYDROPHONE

FIG 3 Finding position by radio acoustic ranging This diagram illustrates use with shore stations

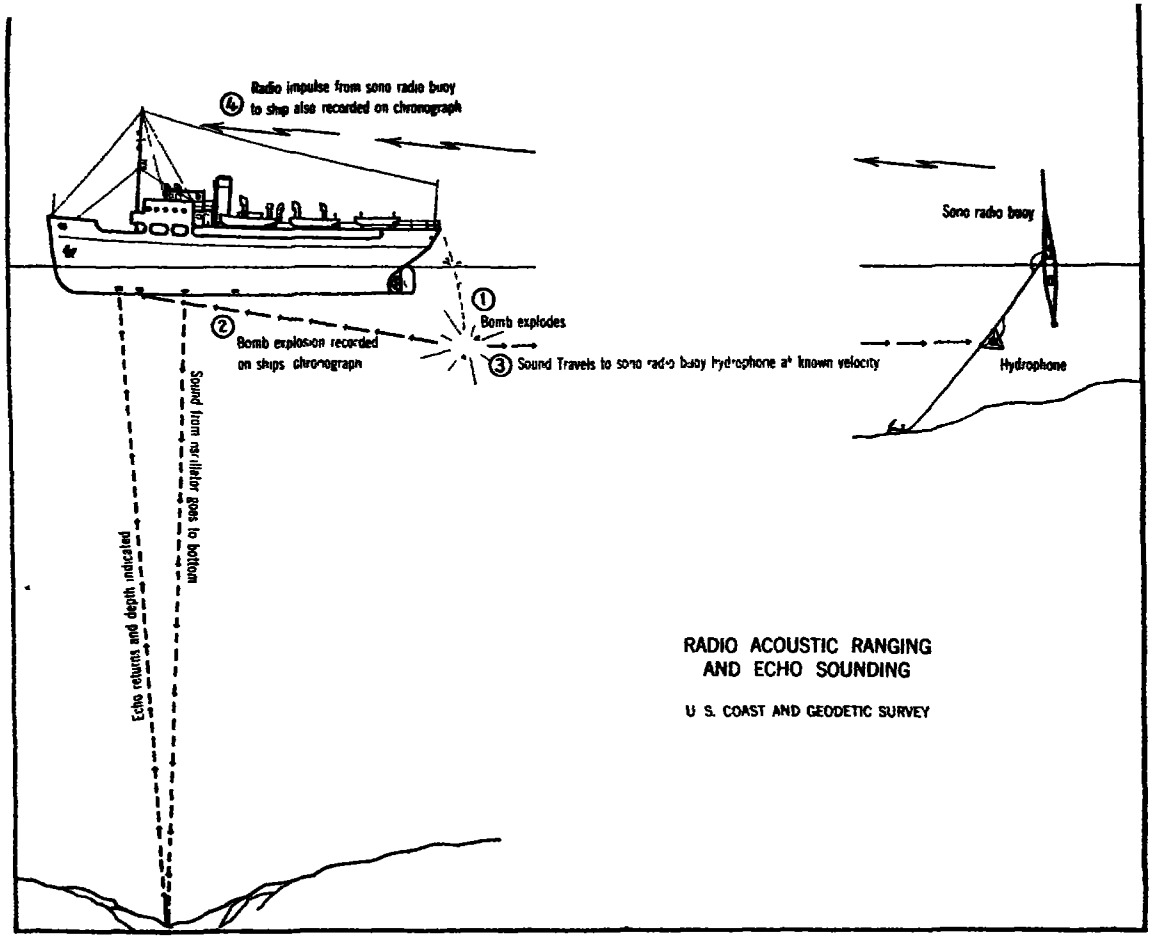
④ Radio impulse from sono radio buoy to ship also recorded on chronograph
Sono radio buoy
① Bomb explodes
② Bomb explosion recorded on ships chronograph
③ Sound Travels to sono radio buoy hydrophone at known velocity
Hydrophone
Sound from oscillator goes to bottom
Echo returns and depth indicated
RADIO ACOUSTIC RANGING AND ECHO SOUNDING
U S. COAST AND GEODETIC SURVEY

FIG 4. Radio acoustic ranging and echo sounding This diagram illustrates use of sono-radio buoys.

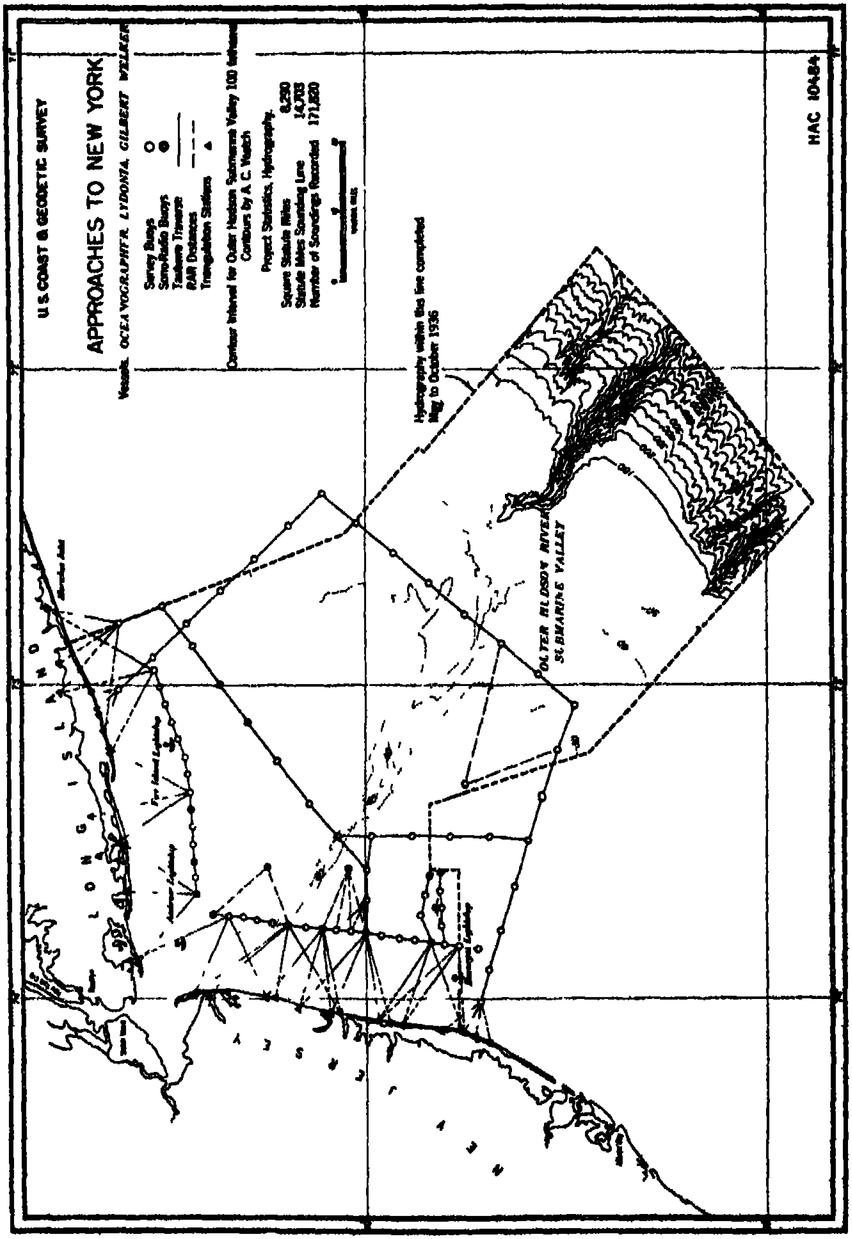
U.S. COAST & GEODETIC SURVEY
APPROACHES TO NEW YORK
Vessels OCEANOGRAPHER LYDONIA GILBERT WELKER
Survey Buoys
Sono-Radio Buoys
Taut-wire Traverse
RAR Distances
Triangulation Stations
Contour Interval for Outer Hudson Submarine Valley 100 fathoms
Contours by A C Veatch
Project Statistics, Hydrography
Square Statute Miles 6,250
Statute Miles Sounding Line 14,703
Number of Soundings Recorded 171,820
Hydrography within the line completed May to October 1936
OUTER HUDSON RIVER SUBMARINE VALLEY
LONG ISLAND
JERSEY
HAC 10484

Fig 5 Survey of approaches to New York, 1936 Illustrates the use of various methods, and shows general configuration of Hudson Submarine Valley

extensive area. The small circles are positions of survey buoys which have been anchored and located by the taut wire apparatus They are used as reference stations by the surveying vessel as the sounding is carried out When the buoys have been anchored approximately in the desired positions, as determined by courses and log distances, the vessel starts at the inshore end of the row of buoys, for instance at the position near Fire Island After anchoring one end of the fine steel wire, the vessel's position is determined by sextant angles measured between triangulation signals on shore, and a run is made along the line of survey buoys, paying out the wire under constant tension The distances between buoys are read from the counter on the sheave as the buoys are passed The directions between the buoys are determined by measuring simultaneously a vertical angle between the horizon and the sun, and an inclined angle between the sun and a pair of the buoys when the latter are on range. This can be done as the vessel steams along full speed and a line of echo soundings also obtained. In the above case (Fig 5) the traverse thus run, extending southeastward 50 miles from Fire Island, thence southwestward 57 miles, thence west-northwestward to the vicinity of Barnegat Lightship had a closing error of 2¼ feet per mile The total length of the traverse was 155 statute miles Supplemental traverses were run where necessary to provide control for the entire area The line of buoys indicated about twelve miles off the New Jersey coast and parallel to the shore was located by frequent visual observations on shore triangulation as well as a taut wire traverse along the line of the buoys The heavy black circles indicate points at which sono-radio buoys were used. This is the first project where the sono-radio buoys were tested for practicability under actual radio acoustic ranging. Station ships were used during the season, as had been done in previous years, so that in case of failure of the new sono-radio buoys no hydrography would be lost Outside of the two lines of buoys parallel to the coasts about twelve miles offshore, all of the work in this area was controlled by radio-acoustic ranging The work of the 1937 season has demonstrated the reliability of the sono-radio buoys and it no longer will be necessary to use station ships for this purpose

The Hudson Submarine Valley is shown roughly on this figure by 100-fathom contours in the area outside of 100 fathoms depth, and 10-fathom contours within

The interesting formation shown in figure 6 was surveyed in 1936 and lies just off the mouth of the Mississippi River

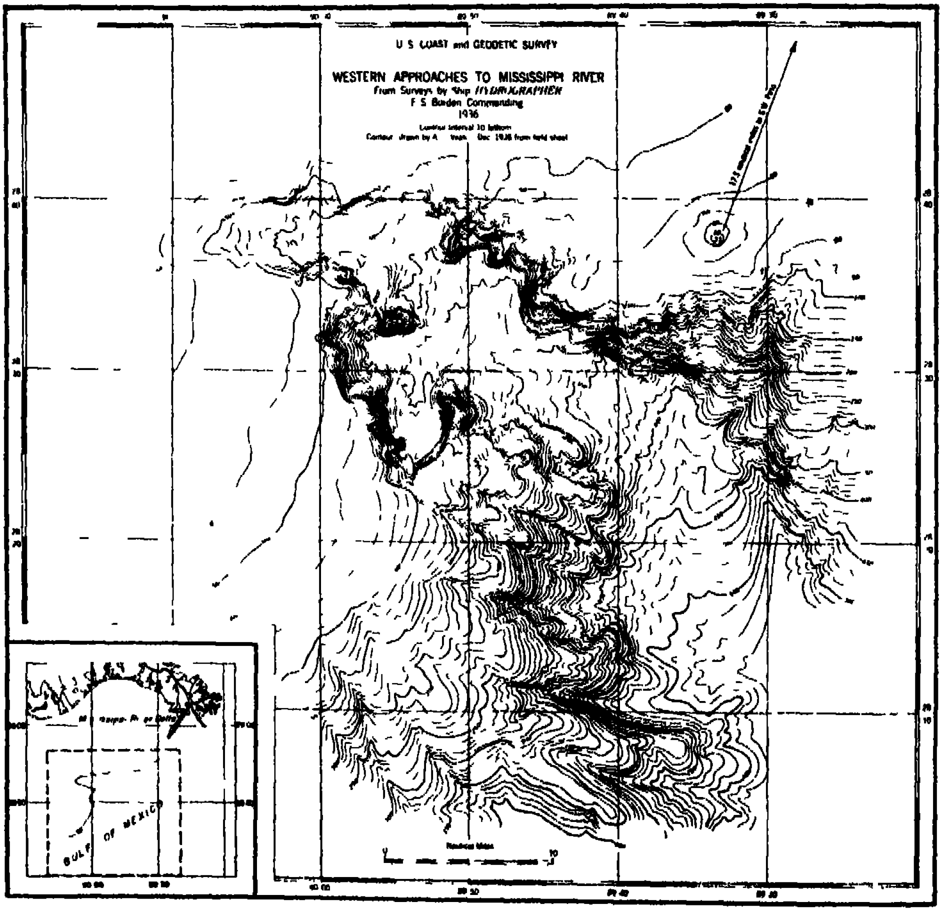
U S COAST and GEODETIC SURVEY
WESTERN APPROACHES TO MISSISSIPPI RIVER
From Surveys by Ship HYDROGRAPHER
F S Borden Commanding
1936
Contour interval 10 fathoms
GULF OF MEXICO
Nautical Miles

Fig 6 A submarine region off the Mississippi River Delta

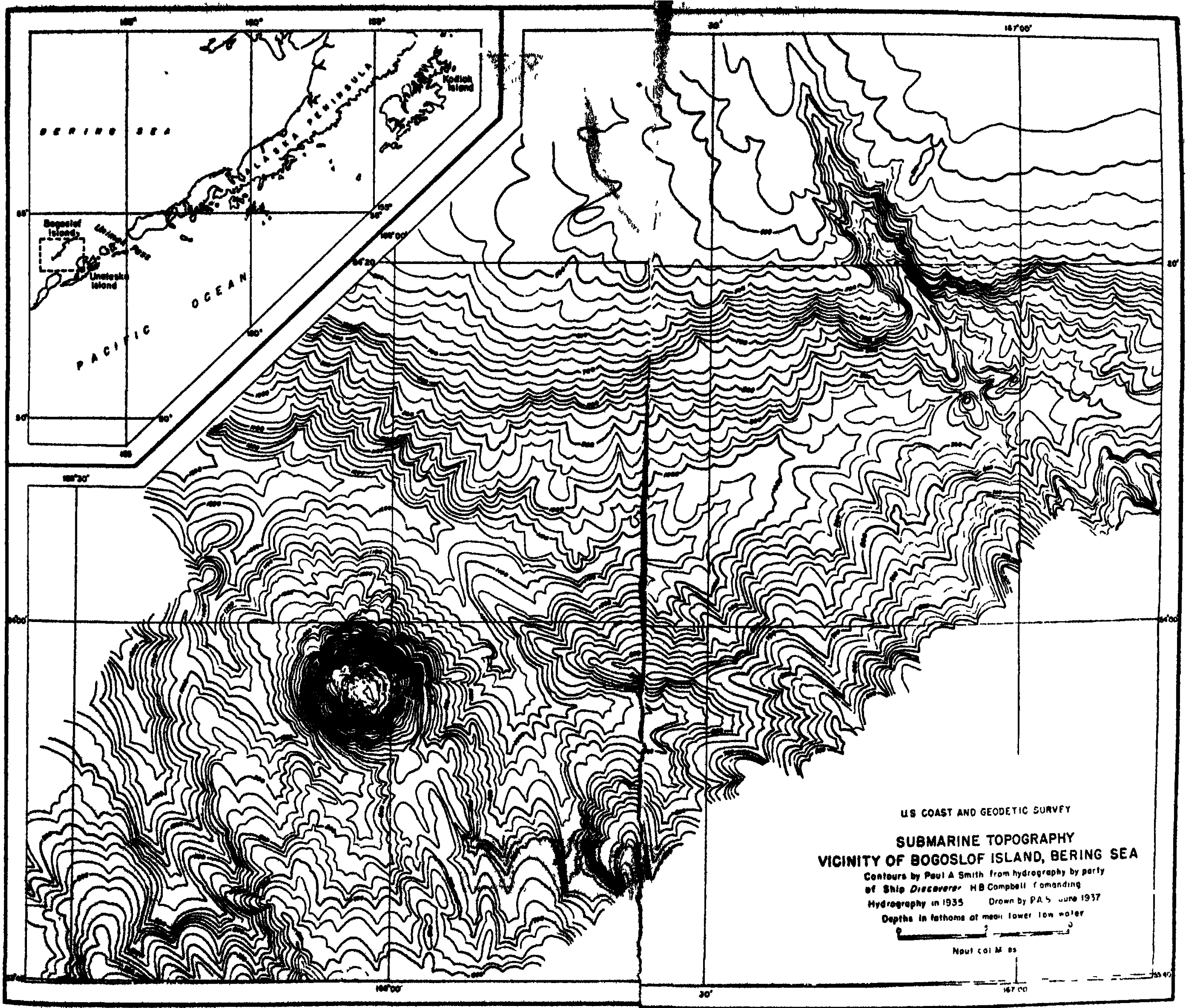
165°
160°
155°
BERING SEA
ALASKA PENINSULA
Kodiak Island
Bogoslof Island
Unimak Pass
Unalaska Island
PACIFIC OCEAN
55°
50°
165
160°
166°00'
54°20'
30'
167°00'
20'
166°30'
54°00'
53°40'
US COAST AND GEODETIC SURVEY
SUBMARINE TOPOGRAPHY
VICINITY OF BOGOSLOF ISLAND, BERING SEA
Contours by Paul A Smith from hydrography by party
of Ship Discoverer H B Campbell Comanding
Hydrography in 1935 Drawn by P.A.S. June 1937
Depths in fathoms at mean lower low water
0
5
Nautical Miles

FIG. 7 Submarine topography, vicinity of Bogoslof Island, Bering Sea

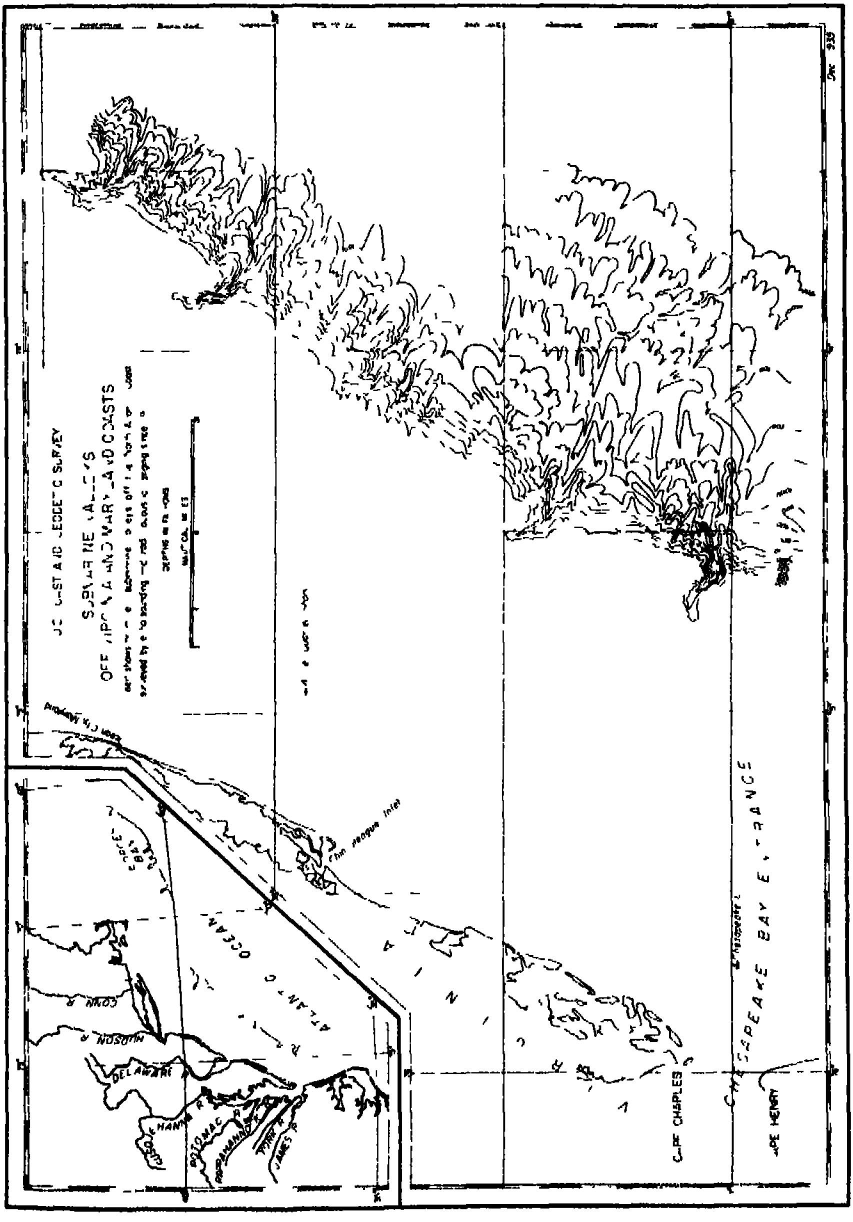

FIG 8 General configuration off Virginia-Maryland coasts

The small hill in latitude 28° 37′ N., longitude 89° 33′ W. has been interpreted as a salt dome uplift by several geologists. Numerous other similar formations have been found along the edge of the continental shelf in the Gulf of Mexico to the westward of this feature

Figure 7 shows a region in the vicinity of Bogoslof Island, Aleutian Islands, Alaska. The contours on this plate are 25-fathom interval. It is of especial interest because it indicates a great volcano rising to the surface of the sea from the ocean floor over 5,000 feet below, around the base of which two large valleys are indicated The valleys apparently were eroded by prehistoric streams subsequent to the formation of the volcano.

Figure 8 shows the general configuration of the Virginia-Maryland coasts

The instruments developed in the course of these surveys have far-reaching significance in addition to their utilitarian value in coastal surveys They supply a long felt need for equipment which will provide the facilities to future oceanographic expeditions for developing and surveying remote regions of the ocean I am thinking especially of the sono-radio buoy, conceived and developed in the Survey This little device can be built at a comparatively low cost, and expeditions equipped with these units can develop submarine features in oceanic areas in detail, using the velocities of sound in sea water as basic lengths. The velocities can be obtained by physical measurements of temperatures and densities In conjunction with the fathometer, or other forms of echo sounders, a well equipped oceanographic expedition should have adequate means at its disposal to survey in detail any feature which may be of interest The portability of the sono-radio buoy is illustrated in figure 9 showing a complete all metal unit used on the Pacific coast. The complete audio and radio parts with necessary batteries are contained in the small drum

I can not commend too highly the valuable reconnaissance work in the deep ocean areas conducted by the United States

Fig 9 All metal sono-radio buoy.

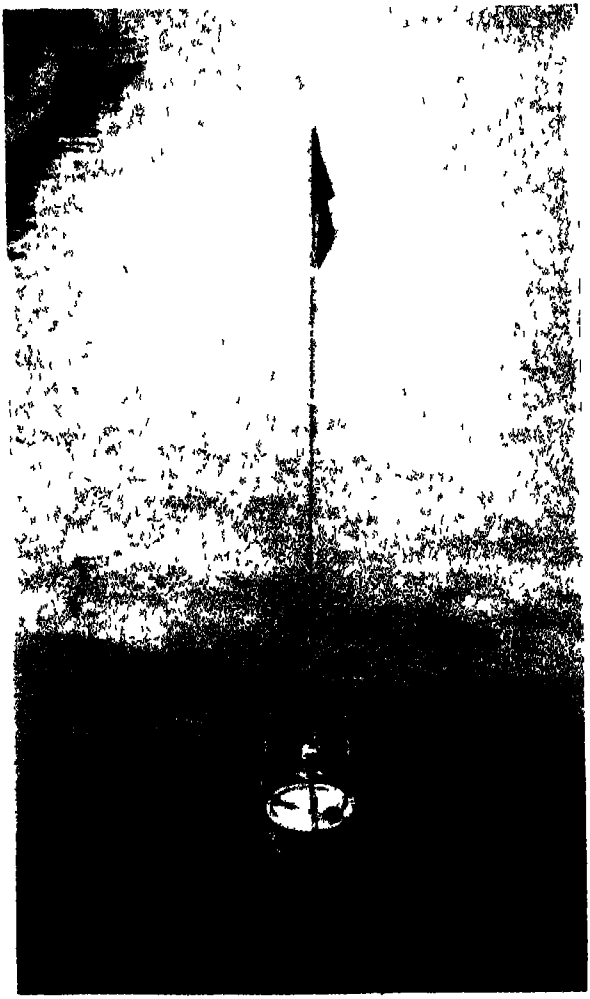

FIG 10 All metal sono-radio buoy afloat

Navy, particularly in the Pacific Ocean This work has demonstrated the importance and the practicability of stimulating and encouraging merchant and naval vessels of other nations to record deep sea soundings on their passages across the oceans The U S Coast Guard also has made valuable contributions to the preliminary knowledge of the submarine topography, especially in the Aleutian Islands region and the

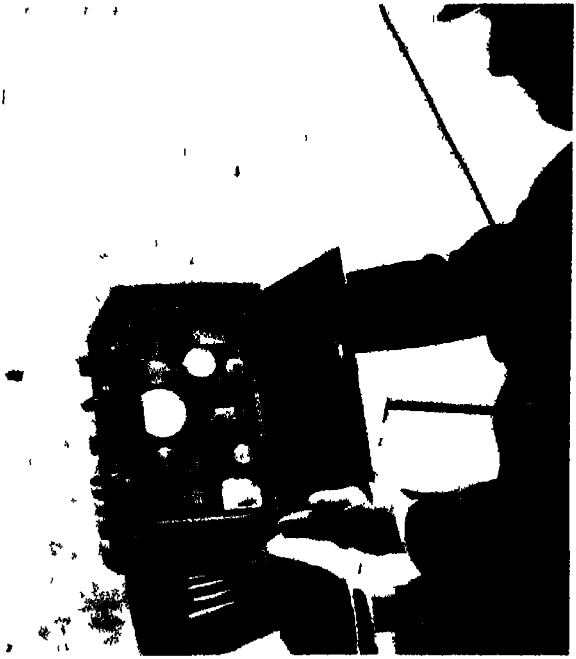

FIG 11 Complete audio and radio units of sono-radio buoy

Bering Sea In such a manner, submerged features of great significance lying outside the continental platforms can be discovered and later surveyed in detail by expeditions equipped with modern devices Truly, we are in a new era of oceanographic exploration The vast regions of the earth's surface lying beneath the sea which have so long been the subject of controversies and speculation soon must give up part of their secrets

PRESENT STATUS OF THE PROBLEM OF SUBMARINE CANYONS *

H C STETSON

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About three quarters of a century ago J D Dana (1), by commenting on the existence of a trough lying off the mouth of the Hudson River, may be said to have put before the geological world a problem to which we still do not possess the answer His data were the relatively rough charts, to judge by their present day successors, furnished by the U S Coast and Geodetic Survey at that period As more of these curious gashes were discovered in various parts of the world, geological discussion was stimulated, although on the older charts the form of the valleys was necessarily shown only as vague indentations in the continental slope (2, 3, 4) Here the matter rested for some years

The recharting of Georges Bank by echo sounding was the spark which revived the question For the first time a really adequate picture of the configuration of the valleys was available It is hard to overestimate our debt to the U S Coast and Geodetic Survey for the continued development of this new technique, and for its application to offshore, deep-water surveying Today we know the shape of these valleys with considerable exactness, we know their distribution, in some cases we know their age, but when the word origin is mentioned geologists can be counted on to line up in two opposing camps It is not so much their size and world wide distribution which is disturbing, it is the as yet unanswerable problems to which they give rise In order to account for their origin we are faced with the necessity of altering the relationship of land and sea to a seemingly

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PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY,
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impossible extent, or else appealing to submarine currents It is becoming apparent, from the data which modern physical oceanography is accumulating, that the forces governing currents in the present-day oceans are not those which could produce the special types required for this work A bottom current of a radically different type, brought into existence by the peculiar conditions of the Pleistocene, has been postulated by Daly This will be discussed later Some of the canyons have been dated by means of fragments of fossiliferous rock dredged from their walls, and they are found to be relatively young Obviously erosional processes on a grand scale were in operation only yesterday, but the clues are just as obscure as though the cutting had taken place in the Cambrian

The multiplicity of the theories and the extraordinary variety of processes, which have been called upon to produce the desired result, give ample testimony that the problem of canyon origin possesses no ready solution The proposals range all the way from the interference of celestial bodies to density currents of an exceedingly complicated type Let us now review the chief explanations which have been offered in the light of what little factual evidence we possess

Before the charts of the recent surveys had been published, many considered the valleys to be tectonic rather than erosional features (5, 6) It is conceivable that a few of them can be explained in this way, but in every instance where an adequate survey has been carried out such has proved not to be the case. Faulting and folding never produce valleys of this shape, and they are certainly not the lunate scars of landslides Most people will agree that they could only have been formed by running water, but where, under the air or under the sea? (7, 8)

The advocates of subaerial origin have two alternatives The land can be elevated or sea level can fall Now that the maximum age of the canyons is known, the first hypothesis has developed so many obvious difficulties that it has few adherents today The extensive grading and general adjustment to present sea-level which the continental shelves display the world over, indicate that they are features of considerable antiquity The canyons which notch their margins are so similar in general configuration and depth that contemporaneous formation is suggested Consequently, under this hypothesis, it is necessary to infer that since the late Tertiary, the continental margins have been simultaneously elevated a matter of 10,000 feet or more, that they stayed there a short time, and then sank again to approximately the original level The affect of such an enormous uplift on pre-existing drainage would have to be obliterated in the same short interval, since no record of any such dislocation remains

Lowering sea level also has its drawbacks It has been suggested that the bottom of one or more of the ocean basins sank and then returned to its former position, much like a piston in a cylinder At present this point is safely beyond the reach of argument, for no one knows anything about the bottom of any one of the major ocean basins.

Hess and MacClintock (9) would change the shape of the hydrosphere, possibly by retarding the rotational speed of the earth, although they admit the difficulties of finding a satisfactory cause Could this be effected, sea level would of course fall, below a certain critical latitude, with a consequent rise above it They start with the premise that no canyons are found polewards of latitudes 55° to 60° It has been argued however that 35° and not 55°–66° is really the nodal point (10, 11). If this is so, the hypothesis breaks down, for plenty of canyons are known north of 35°, and for that matter south as well

One more method of lowering sea level has been suggested —the Pleistocene ice sheets The commonly accepted estimate of the reduction of sea level by this means is of the order of 300 feet Shepard (12), however, by enlarging known areas of ice accumulation, assuming an average thickness of four miles for the whole sheet, and chiefly by postulating an ice cap for the polar basin, raises the estimate to what the conservative considers the almost astronomical figure of 3,000 feet We have no yardstick to serve as a basis for discussion of much that he proposes However, there are several factors in connection with the formation of an Arctic ice cap which deserve mention This cap, to have any effect on sea-level, would have to extend to the bottom, a distance of two miles or more Otherwise accumulating snow and ice on the surface would only sink the sheet deeper in the ocean, thereby displacing more water Furthermore, the Arctic is today a region of little precipitation, and with a perpetually frozen ocean, surrounded by land masses covered with snow and ice, would it not be even more arid? At best accumulation would be thin compared to that farther south In support of his hypothesis Shepard cites some recent work by the Russians showing that an ice sheet flowed southwards over northern Eurasia However, the whole coast is bounded by an exceptionally wide continental shelf The sea over this shelf is shallow, and, made even shallower during the Pleistocene by the withdrawal of water elsewhere, probably froze solidly to the bottom Might not this platform be the center of accumulation for the southward flowing ice over Siberia?

Submarine currents of different types have frequently been suggested as the excavators of the canyons (13, 14, 15) In 1936, bottom currents in two of the Georges Bank canyons were measured by means of an Ekman meter (16) The normal, rotary system of tidal currents on the continental shelf is upset, and on the bottom the currents were found to flow up and down the valleys Yet even here, where the currents at the surface are exceptionally strong, the highest recorded velocity was 11 08 cms sec , or a little more than 2 of a knot at the peak of the flood tide Spring tides at the surface have a velocity 40 per cent greater than the neaps, during the course of which the reading was made If we arbitrarily increase this velocity by the above amount we get only 15 51 cms sec Considering the indurated nature of some of the beds of which this part of the continental shelf is composed, it does not seem probable that currents with velocities such as these would be particularly competent agents of erosion They would move the finer grade sizes in an unconsolidated deposit, and by so doing might serve to check or retard present day deposition, but this is the most effective rôle which they can be expected to play The tidal currents were strong enough to completely mask other types which may have developed an on and off-shore component, and it is to be expected, in coastal waters, that they will always have the greater velocities We are justified therefore, in eliminating tidal currents from the list of factors responsible for the east-coast canyons, and it is probable that further work will show this to be true for all canyons

As was stated above, modern physical oceanographers tend to look with disfavor on the theory that these canyons could have been cut by present-day currents or by currents in the past actuated by similar forces (17) Localized currents with a strong on and off-shore component would be required, and aside from tidal currents, it has not been demonstrated that any such exist Furthermore the conditions necessary for their production and maintenance are not fulfilled by the data which are gradually accumulating

Daly has argued for a radically different type of density current (18) During the times of lowered sea level of the Pleistocene, large areas of unconsolidated, fine-grained deposits on the continental shelf and slope, which formerly had lain below wave base, came within the reach of wave action Large quantities of sediment were thrown into suspension by the storms of that period This heavier, denser water would first seek the depressions of the shelf It would concentrate in them and run down the slope with greatly accelerated motion. Sufficient velocity might be developed to cut grooves, and later, trenches Daly also considers the possible erosive effect of submarine mud flows which might be set in motion by the drag of this current of muddy water on the bottom In a recent paper, Kuenen strongly supports the idea (19) He finds, by tank experiments, that currents of this type will cut grooves in an unconsolidated "slope," and also that they do not diffuse readily with the surrounding water. There is no question but that this mechanism could operate in the open sea The crux of the matter is, of course, the amount of energy available for the work translated in terms of velocities, and the hardness of the rocks which must be cut The rocks of the Georges Bank canyons are known in more detail than those of any of the others (20). The upper part of the walls stand as cliffs with many outcropping ledges The stratigraphic succession, as far as it is known, runs from the upper Cretaceous to the late Pliocene. A large proportion of these beds consist of clays, silts, and greensands which show little consolidation, but there are several beds of hard sandstone Granite, as well as semiconsolidated sediments, has been reported from the walls of some of the California canyons (21) The presence of resistant rocks is the chief stumbling block which this theory has to overcome, and may prove a serious difficulty should many hard formations be found in future dredging.

The foregoing comments are not intended to be offered as purely destructive criticism, but to emphasize the point of view that there is no one universal explanation for the problem of canyon origin The extreme differences of opinion which exist today are indications that in the future we will come to recognize a combination of causes Also, it may well be that different canyons have been formed by different means Should we assume a similar mode of origin for gorges cutting the seaward margin of broad, well-graded shelves; for those which head almost at the shoreline, and for those which lie at the outer end of a trench leading from some large river? Continued dredging and continued charting will help provide the answer. Without additional facts further discussion can not advance beyond the stage of hypothesis

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THE TECHNIQUE OF SECURING UNDISTURBED CORE-SAMPLES OF THE OCEAN BOTTOM

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THE problem of securing core-samples of the bottom at depths as great as 1000 fathoms (6000 feet) is not particularly difficult. The mechanical and manipulative factors involved in making soundings down to this relatively moderate depth are not so great as to preclude the use of the kinetic energy of a heavy weight, or the employment of the heavy lines necessary to handle it, nor is the time element particularly significant Beyond this point the difficulties multiply as the depth increases, until any attempt to bring up adequate cores from below 3000 fathoms (18,000 feet) is a feat of coördinated mechanical engineering and seamanship of no mean order Kinetic energy can no longer be relied upon to do useful work at the bottom, and the various stresses and masses involved inevitably increase so much that efforts to keep them at a minimum assume a dominant importance.

The sounding cable itself develops complications of its own as its length increases Hemp rope will grip a capstan-head easily and can be readily stowed in a relaxed condition beyond the hoisting mechanism, but the weight of any adequate apparatus, together with the strain of pull-out from the bottom, demands a rope whose bulk and buoyancy soon defeat its purpose The cable ships meet this situation by covering steel wires with hemp, and using a capstan-head 7 feet in diameter, beyond which the rope is coiled in large tanks. In 1936 I used part of such a rope that was 20 miles long. Wire rope cannot be taken over a capstan-head under strain and then coiled satisfactorily From the standpoint of strength and storage, wire rope is the most satisfactory, but its weight brings up other problems No wire rope is able to sustain its own weight of 6000 fathoms, required to sound the greatest deep (5900 fathoms), and retain any reasonable factor of safety, to say nothing of the weight of apparatus or the strains of the pull-out, or the movement of the ship at the surface These considerations necessitate a tapered rope whose weight increases only in proportion to the strength required This greatly increases the difficulty of spooling or winding on the winch drum, for unless spooling is smooth and regular in the underlying layers, overlapping ropes will be crushed by the enormous pressures developed These same pressures develop great lateral stresses which tend to burst the flanges of the winch drum Finally, winches of such great capacity are not common, and none exist on large, steady ships

Therefore the problem of securing satisfactory core-samples of the bottom of the great deeps resolves itself into many mechanical considerations, involving the devising of a tool possessing a great supply of energy which is released and controlled entirely automatically on reaching the bottom, and which is lowered by means of a special cable and winch The cores obtained must be undistorted, and the material must reach the laboratory in the exact condition in which it left the bottom Furthermore, considerations of expense demand that this gear be adapted to use from any ship—not only from one especially built for the purpose. The coring apparatus itself must be as light as possible and yet very rugged As it is not feasible to send any considerable energy down through much sea-water or to operate complicated machinery in this very corrosive substance, the apparatus must possess within itself the energy necessary to do the required work, and this energy must be reliably controlled and accurately directed As the time element becomes increasingly important with increasing depth, this work must be accomplished as expeditiously as possible

These essential features have been more or less completely met by an apparatus which has been in use since the summer of 1935, and a special cable of 5400 fathoms and a winch to handle it are now being constructed This coring apparatus consists of 5 principal parts a gun, a cartridge, a firing mechanism, a water-exit port, and a bit The mechanical details are fully described in the *Bulletin of the Geological Society of America*, Vol 47, pp 675–684, May 1936

SOUNDING PROCEDURE

The apparatus is assembled and aligned in chocks on the deck, the firing mechanism cocked, and the safety-pin inserted A cartridge is loaded in accord with the anticipated need If it is the first sounding in a new locality, it is advisable to provide rather less than the anticipated required energy Subsequent loads may be increased as circumstances warrant When all is ready, the cartridge is fastened in place and the gun "loaded," by sliding the bit toward the gun, and the shear pin is put in place The apparatus is then hoisted over the side A man picks up the bit at the cutting edge, and, as soon as the gun clears the rail, he drops his end over the side into the water The apparatus is immediately lowered until only the gun is out of the water, this prevents swinging against the ship's side Finally, the safety-pin is pulled out and the apparatus is lowered to the bottom When the apparatus returns to the surface, if it has fired, the gun and bit will be hanging separately at the end of their respective cables, the bit supported in the stirrup If they are not so separated, and it is desired to bring the apparatus aboard, the safety-pin must be inserted at the earliest possible moment while the apparatus is hanging clear of the ship Once this pin is in place the gear may be brought aboard with safety.

The 14 cores shown in Fig 1 were taken from the canyons off the Maryland-Delaware coast in 1935, and the 11 cores in Fig 2 were obtained from the North Atlantic between Newfoundland and Ireland in 1936. These will be discussed by Dr Bradley

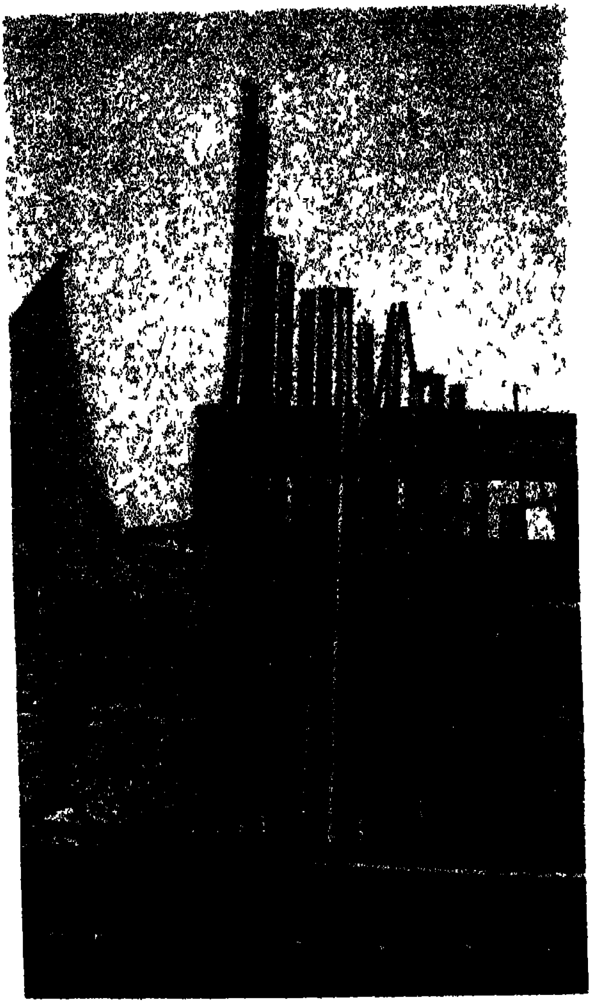

Fig 1 Cores from the canyons in the continental shelf off New Jersey, Delaware, and Maryland Maximum length 8 ft 8 in Depths 200–1250 fathoms

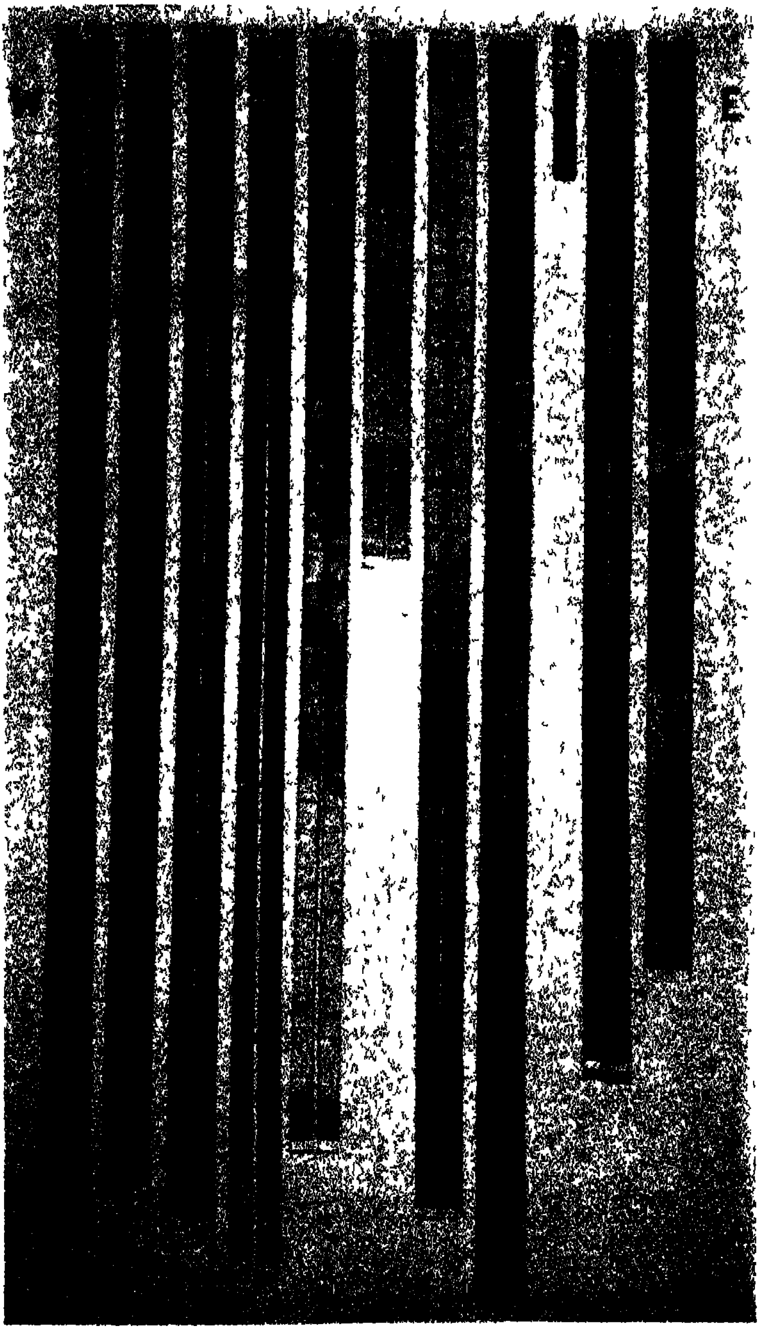

Fig. 2 Cores from the North Atlantic, Newfoundland to Ireland, arranged as taken from West to East. Maximum length 10 ft. Depths 700–2650 fathoms.

Cores have since been obtained from the eastern continental slope of the United States, and beyond, and also from the Bartlett Deep between Jamaica and Cuba at a depth of 2800 fathoms, and some have been taken from the Gulf of Mexico

An essential requirement for a deep sounding is that the ship remain stationary with respect to the bottom It is true that drift may then take the wire off somewhat, but this is a lesser evil than extensive movement of the ship by wind or surface current

The best way to be certain that the ship *is* remaining stationary is to put out one or more buoys, despite the depth, and after the buoy has taken its permanent set to keep the ship oriented with respect to it This is a laborious procedure, to be sure, and can only be done easily by a ship having ample power, and preferably two propellers If a particular area is of special interest, and several soundings within a small radius are desired, the establishment of such a reference is well worth the added trouble

THE GEOLOGICAL SURVEY'S WORK ON THE PIGGOT NORTH ATLANTIC DEEP SEA CORES*

W H BRADLEY, M N BRAMLETTE, J A CUSHMAN, L G HENBEST,
K E LOHMAN, AND P D TRASK

The United States Geological Survey

A SERIES of 11 cores from the North Atlantic sea bottom between the Newfoundland Banks and the banks off the Irish coast have been studied by a group of geologists of the Geological Survey These cores were taken by Dr C S Piggot of the Carnegie Institution's Geophysical Laboratory from the cable ship "Lord Kelvin" with the explosive type of core-sampler, which he designed (1) This preliminary report is based largely on the results obtained by M N Bramlette, who studied the lithology, and Jos A Cushman, who studied the foraminifera

The geographic position, the depth of water at each station, and the length of core obtained are given in table I

TABLE I

GEOGRAPHIC POSITION, DEPTH OF WATER, AND LENGTHS OF CORES TAKEN FROM NORTH ATLANTIC SEA BOTTOM

Station and core No	Latitude—N	Longitude—W	Depth of water in fathoms	Length of cores in meters
3	46° 03′ 0″	43° 23′ 0″	2575	2 82
4	48° 29′ 0″	35° 54′ 30″	2165	2 72
5	48° 38′ 0″	36° 01′ 0″	2640	2 82
6	49° 03′ 30″	32° 44′ 30″	2260	2 93
7	49° 32′ 0″	29° 21′ 0″	1780	2 62
8	49° 36′ 0″	28° 54′ 0″	700	1 24
9	49° 40′ 0″	28° 29′ 0″	2050	2 77
10	49° 45′ 0″	23° 30′ 30″	2295	2 97
11	48° 38′ 0″	17° 09′ 0″	2640	0 34
12	49° 37′ 0″	13° 34′ 0″	1770	2 43
13	49° 38′ 0″	13° 28′ 0″	1070	2 22

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* Published with the approval of the Director, Geological Survey

Core No 3 was taken just off the Newfoundland Banks in the blue mud zone, but all the others were taken in parts of the ocean where the bottom is blanketed with Globigerina ooze Core No. 8 was taken on the mid-Atlantic ridge and core No 11 struck volcanic rock

In about 20 representative samples from each core the percentages of calcium carbonate, clay and silt, sand, and coarse sand were determined Also the relative abundance of foraminifera, coccoliths, and diatoms was estimated in these samples Material between these guide samples was examined microscopically, especially in certain critical zones

Two zones in which acid volcanic ash (refractive index near 1 51) is common were found. The upper one was found in all the cores except No 11, but the lower one has thus far been found only in the lower part of cores 4–7 Although in most of the cores the upper ash zone is restricted to the upper part, in core No 3 it is represented by scattered shards, but the core, despite its length, apparently did not reach that part of the ash zone where the shards are most abundant This upper ash zone serves to correlate the cores and the lower ash zone, where found west of the mid-Atlantic ridge, reinforces the correlation

Besides the zones of volcanic ash four other zones of distinctive lithology were found These zones are characterized by a relative abundance of sand and pebbles, by a smaller percentage of calcium carbonate, and by a sparsity of organisms—foraminifera and coccoliths. They also have a distinctive texture The pebbles are sub-rounded to angular and include a wide variety of rock types—sandstone, gneiss, soft shale, and limestone—of which limestone is the most common. Some of the pebbles are as much as 2 centimeters across. These zones are interpreted as glacial marine deposits formed during the Pleistocene glacial epoch when continental glaciers were eroding the land Drift ice from the continental glaciers apparently transported considerable quantities of rock debris far out into the ocean basin. Larger boulders, some with facets and striæ, have been dredged in latitudes as far south as the Azores, and have been interpreted as transported by Pleistocene ice drift.

Glacial marine deposits closely similar to these were described by Phillippi (2) from the South Atlantic off the margin of the Antarctic shelf ice From that locality where they are now forming, Phillippi showed that they extended northward into the South Atlantic beneath a cover of first diatom ooze and, farther north, of Globigerina ooze

In the equatorial part of the Atlantic, Schott (3) interpreted an abrupt change from a surface layer of warmer water foraminiferal fauna to an underlying colder water fauna as the boundary between post-glacial deposits and deposits of the last glacial epoch In some cores he found, below the deposits characterized by a colder water fauna, other deposits containing a warmer water fauna which he interpreted as inter-glacial

Between the glacial marine zones found in the North Atlantic cores the sediments consist chiefly of Globigerina ooze or limy clay much like that which is forming today in the same area

The uppermost glacial zone is represented in all the cores but Nos 3 and 11 and lies just below the upper volcanic ash zone. Core No 3, though nearly 3 meters long, did not reach the base of the upper ash zone and so of course did not reach the top of even the highest glacial zone Core No 11 is evidently too short to have hit either the ash or the glacial marine deposits In cores 4–7 the glacial zones are relatively thin and are spaced at approximately equal intervals Between the third and fourth glacial zones (in descending order) is the lower volcanic ash Only the uppermost glacial zone has been identified east of the mid-Atlantic ridge Other glacial marine deposits are recognizable but their correlation is less certain.

Cores 3, 8, and 11 are markedly different from the others Core No. 3 is distinctive for its uniformity in texture and composition With the exception of three thin clay layers that are widely spaced, this core consists of about equal amounts of clay and silt-sized clastic material and clay and silt-sized calcium carbonate particles Coccoliths are rather common throughout, but foraminifera are relatively rare

In contrast core No 8 is characterized by an abundance of coarse sand and pebbles, by only the coarser volcanic glass shards which are not common, by abundant foraminifera, and by very little matrix of clay and silt sizes According to our interpretation currents move across this part of the mid-Atlantic ridge (Faraday Hills) with sufficient velocity to winnow out most of the fine-grained material and carry it into deeper basins such as that where core No 9 was taken Core No 9 is characterized by a predominance of very fine grained material

Core No 11 penetrated only about 15 centimeters of Globigerina ooze before encountering a deeply altered volcanic rock which it penetrated about 23 centimeters Preliminary examination suggests that this rock may represent a submarine flow of basaltic rock

It is evident from the large differences in depth below the ocean floor to the top of the latest glacial marine zone that the rate of deposition differs widely from place to place In cores 4, 5, and 7, for example, the top of the latest glacial zone is about 30 centimeters below the top, and if the last glacial epoch is taken as 20,000 years ago then the post-glacial deposition in these three cores was at the rate of approximately 20,000 years per foot. As core No 3 did not reach the glacial zone, the rate of deposition there must have been something more than 10 times as rapid On the mid-Atlantic ridge the rate was somewhat slower and in some areas east of the ridge the rate seems to have been several times as rapid as prevailed generally west of the ridge

Iselin (4) in studying some bottom cores off the Irish coast concluded that the marked decrease in carbonate content below about 25 centimeters represented deposits of a glacial epoch. He estimated the rate of accumulation in that locality to be about 1 centimeter per 1000 years or 30,000 years per foot

Schott (5), after studying the cores obtained on the Meteor expedition in the equatorial Atlantic, estimated the average rate of accumulation by the depth to the top of the deposits formed during the last glacial epoch to be 25,000 years per foot His estimates for various cores ranged from 14,000 to 57,000 years per foot

The biologic evidence now available is Cushman's interpretation of the temperature conditions revealed by the pelagic foraminifera at successive levels in the cores. He found that at some levels the foraminifera indicated warmer water conditions than prevail in that part of the ocean today, whereas at other levels they indicated much colder water than today At other levels they indicated conditions nearly like those of today Where the physical evidence indicates glacial marine zones the foraminifera indicate a cold water environment The interglacial zones, except the latest one, all show warm water foraminifera faunas The fact that the uppermost or latest interglacial zone contains a cold water fauna may mean that the uppermost two glacial zones indicated by the physical evidence are really only phases of the glacial stage—the last or Wisconsin stage

Below the lowest glacial marine zone encountered in the cores the foraminifera indicate in each core conditions as warm as today or warmer.

From the evidence thus far available, we conclude that these long cores have penetrated sediments that represent not only all Post-Pleistocene time, but some have penetrated three, or perhaps four, glacial stages and three, or perhaps four, interglacial stages of the Pleistocene epoch None of the foraminifera in the bottoms of the cores suggest Pliocene species

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MARINE GRAVIMETRIC METHODS AND SURVEYS

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I INTRODUCTION

IN 1923 Dr F A Vening Meinesz made a voyage from Holland to Java on board the Netherlands Submarine K II, during which he made pendulum gravity observations at 32 stations Twenty-six of these were made while the submarine was submerged in the open ocean, and they are the first gravity measurements sufficiently accurate for modern geodetic purposes which were ever made at sea

The great need of gravity data in oceanic regions had been pointed out by Bowie (1), Hayford (2), Bauer (3), and others Many workers had attempted to measure gravity on ships at sea, but it had seemed so futile to attempt to operate a gravity pendulum on the unsteady base provided by a ship that the efforts had been directed toward development of some substitute to replace the standard pendulum method Siemens (4) on the ship *Faraday* in 1875 used a gravity barometer in which the weight of a column of mercury was balanced against the pressure of an enclosed body of gas, and also a device in which a steel spring supported a mercury column His observations are invalidated by causes not clear even now, but his instruments incorporated many principles now used in the most modern gravimeters *

Hecker (5), using a method which Mohn (6) had developed for obtaining gravity corrections to barometer readings at stations of the Meteorological Service of Norway, made three extensive voyages between 1901 and 1909 on which he estimated the force of gravity by comparing the atmospheric pressure determined from the boiling point of water with that given by a mercurial barometer. Bauer (3) carefully reviewed the work of Hecker while considering inclusion of gravity measurements in the program of the *Carnegie*, and concluded that "the problem of obtaining sufficiently reliable ocean gravity results still awaits solution." He expressed strongly the hope that the great importance of getting gravity values would lead someone to discover a better method for ocean gravity work

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* It is a shock now to realize that Siemens was measuring gravity to compute from it the depth of water

Briggs (7) made measurements of gravity from Sydney to San Francisco in 1914, and from New York via Panama to San Francisco in 1915. His apparatus contained a gas maintained at constant temperature and volume, and he measured the height of the mercury column needed to balance the pressure

Duffield (8) made gravity measurements during voyages from England to Australia and back in 1914, and again in 1922-23. He used gravity barometers, photographic recording barometers, and gravity spring balances, but his results apparently lack the accuracy required for geodetic work.

II DEVELOPMENT OF THE MEINESZ APPARATUS

From the very beginning of gravity measurements the pendulum has been the standard instrument for gravity surveys on land All earlier workers had considered as axiomatic the impossibility of operating gravity pendulums on ships, but Meinesz approached the problem of marine gravity measurements with years of experience in pendulum gravity surveys In the years 1912 to 1921 the Gravity Survey of Holland experienced difficulty in finding fixed bases for the pendulum apparatus at many stations, and the consequent unsteadiness had to be taken into account. By swinging two pendulums in the same plane for each observation, it was found possible to eliminate the effects of horizontal accelerations in this plane (9) The success of this effort led to an investigation of the possibility of using the apparatus on board a ship

The first tests at sea were made on a small steamer on the North Sea Canal near Amsterdam with a Stuckrath four-pendulum apparatus They showed the method to be feasible provided the visual observation of the coincidences could be replaced by photographic recording, and further that the motion of the ship could be held to a small value. Professor van Iterson suggested that a submerged submarine would be free from the disturbances of wave action, and a very successful test was made on a submarine in the roadstead at Helder in May 1923 Plans were then made for the voyage to Java in the autumn of 1923, in coöperation with the Netherlands Navy On this voyage, which marks the real beginning of accurate gravity measurements at sea, pendulum gravity measurements were made with an accuracy approaching that of standard land measurements

As a direct result of this work, over 1,200 gravity stations at sea have now been completed, more than 800 of them by Meinesz himself. Following the lead of the Netherlands Navy, the navies of the United States, U. S S. R, Italy, France, and Japan have given support, each having participated in one or more surveys

The Stuckrath apparatus used on the cruise of the K II was replaced in 1925 by a new instrument especially designed for measurements at sea This apparatus underwent successive modifications, primarily in details such as gimbal suspension, mechanism of the photographic recorder, which were thoroughly tested on the cruises of the Netherlands submarines K XI and K XIII in 1925 and 1926. The form of the apparatus which has been accepted as final was reached prior to the cruise of the U S submarine S-21 in 1928 The final form of the apparatus is described by Meinesz (10) It contains three half-second bronze pendulums, as nearly isochronous as possible, which all swing in the same plane It contains two auxiliary pendulums provided with internal damping which are intended to indicate the deviations of the apparatus from the vertical—one in the swinging plane of the gravity pendulums and one at right angles to it The case of the pendulum apparatus is well insulated against heat transfer but is not airtight Inside the case are a hygrometer, a mercurial thermometer inside a dummy pendulum, and a bimetallic strip thermometer By means of a mechanism operated from outside the case, it is possible to raise the pendulums and clamp them in spring supports when they are not in use, to lower them into the swinging position, to give them any desired initial amplitudes of swing, and to start them swinging in the same or in opposite phase as desired.

The light box, which contains the arrangement for photographic recording of the pendulum oscillations, is mounted directly above the pendulum case and the entire unit is supported in gimbals The light box contains the supply of photographic paper, a spring motor for moving the paper during an observation, a lamp to provide illumination for recording, and shutters or light valves actuated by break circuit chronometers for making momentary eclipses of the beam of light These eclipses serve as the time reference marks from which the periods of the gravity pendulums are calculated

The beam of light which enters the pendulum case from the light box is divided into five parts, three of which are reflected from mirrors attached to the gravity pendulums Let θ_1 and θ_3 represent the angular displacements of the two outermost pendulums, and let θ_2 represent that of the middle one The optical system provides for continuous recording of the differences $\theta_1 - \theta_2$ and $\theta_3 - \theta_2$, also θ_2, the inclination of the middle pendulum to the vertical as indicated by the damped pendulum which operates in the swinging plane. The two other light beams record the temperature indication of the bimetallic strip and the tilt perpendicular to the swinging plane as indicated by the second damped pendulum. A photograph of the Meinesz apparatus is shown in figure 1.

The angular differences $\theta_1 - \theta_2$ and $\theta_3 - \theta_2$ are regarded by Meinesz to represent the angles of elongation of two fictitious pendulums, and it can be shown that, to the first order of small quantities, these fictitious pendulums are independent of horizontal accelerations in the swinging plane.

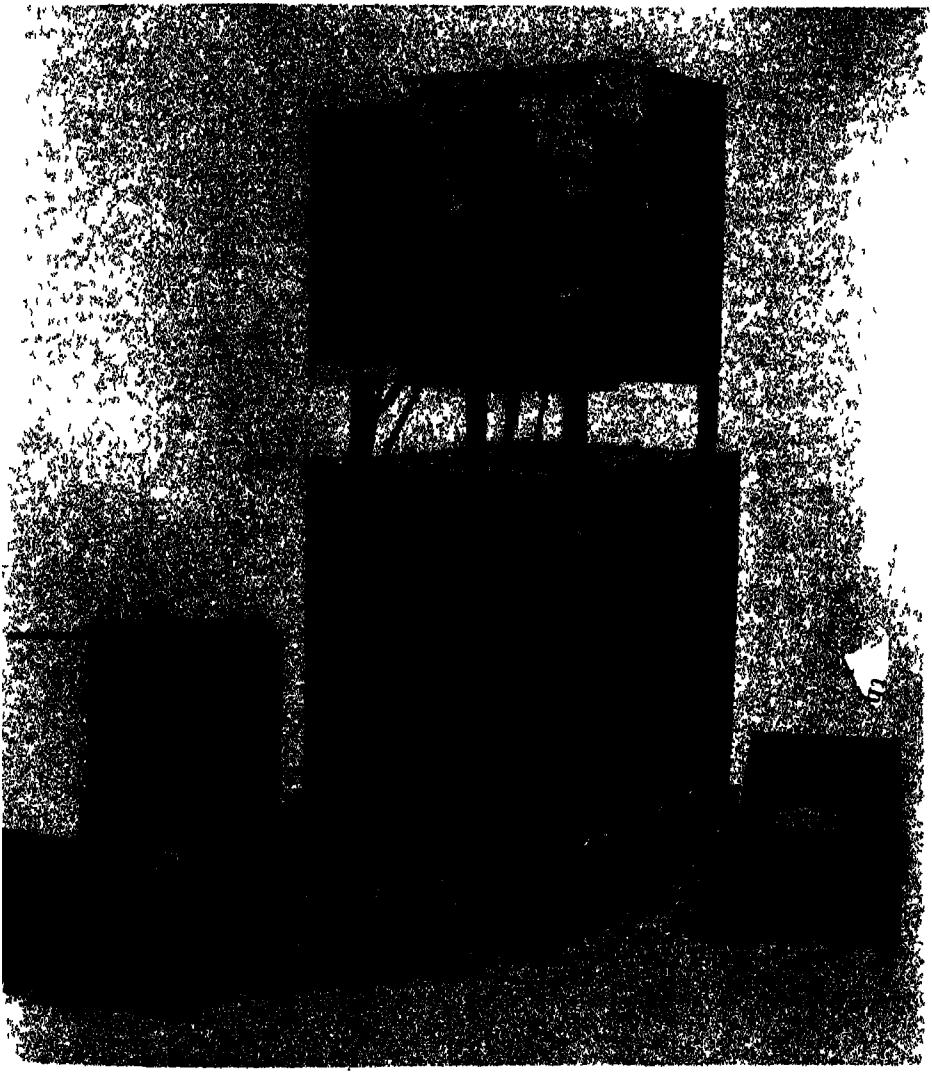

FIG 1 Photograph of the Meinesz pendulum apparatus

The chronometers used for measuring the periods of the pendulums produce eclipses in the light beams which record photographically the motions of the pendulums The rates of these chronometers are determined by comparisons with radio time signals twice daily Comparisons are made by connecting one of the break circuit chronometers in series with the headphones of the radio receiver and noting coincidences between the chronometer and the time signal. For rhythmic time signals, a mean-time chronometer was used, while for ordinary signals a mean time chronometer with rate deranged to give several coincidences during the period of time signal transmission was substituted After reception of the time signal the chronometers were intercompared, also by a coincidence method.

The duration of a gravity observation with the Meinesz apparatus is about 30 minutes, and all observations are made with the ship submerged and travelling at constant speed and depth It is necessary to know the magnitude and direction of the velocity of the ship in order to apply the Eotvos correction for the alteration in gravity produced by the east-west component of velocity The depth of submergence depends upon the condition of the sea, and should be sufficient to reduce the effect of wave motion below a certain minimum value

III Summary of Surveys Using the Meinesz Method

The following table includes all marine gravity surveys known to the author on which the Meinesz apparatus, or instruments of other design embodying the principle of the fictitious pendulum, have been used The complete results of all surveys have not yet been published. Information for each survey is listed under the following headings·

A Date, name of ship, and number of stations occupied.
B Personnel of scientific staff, and reference to publications
C. Region surveyed.
D. Description of apparatus used.

1 1923, Sept 18–Dec 24 Netherlands K II Number of Stations 32
Meinesz, Reference 11, Vol 1, Chapter 2
Holland via Suez to Java
Apparatus Stuckrath, 4 bronze pendulums swinging in 2 planes Photographic recording which recorded motion of each pendulum separately Cradle to eliminate effects of ship roll added in Gibraltar One chronometer used with relay between it and the light valve

2 1925, Oct 15–Nov 12 Netherlands K XI Stations 12
Meinesz, Reference 11, Vol. 1, Chapter 3
Holland to Alexandria
Apparatus Meinesz 3 pendulum design, recording fictitious pendulums directly, decreasing labor of reduction Accuracy increased by use of 2 chronometers Unnecessary to open pendulum case for any operation Light box separate from pendulum case with cradle for removing roll of ship Echo soundings adopted as standard part of program on this voyage

3 1926, May 27–Dec 13 Netherlands K XIII Stations 128
Meinesz, Reference 11, Vol 1, Chapter 4
Holland via Panama to Java
Apparatus Meinesz, improved by complete gimbal suspension, light box atop pendulum case, cable release for shifting paper speeds, and agate bearings and steel points on damped pendulums to decrease friction

4 1927, Feb 3–Feb 15 Netherlands K XIII Stations 28
Meinesz, Reference 11, Vol 1, Chapter 4
Java Deep
Apparatus Same as for No 3

5. 1928, Oct. 2–Nov. 27 United States S-21 Stations 49
Meinesz and Wright, Reference 12
Washington to Greater Antilles, Gulf of Mexico, and return
Apparatus Meinesz, with improved light box Light valves

operated on smaller current, eliminating necessity for relays between light valves and chronometers This form of the Meinesz apparatus was accepted as final.

6. 1929, June 12–Aug 12 Netherlands K XIII Stations 232
Oct. 8–Nov 14
1930, Jan. 2–Feb 15
Netherlands East Indies
Meinesz; Reference 11, Vol 1, Chapter 5
Apparatus Meinesz

7 1929, Sept 3–Nov 29 *Carnegie* Stations 5
Forbush, Reference 13
San Francisco to Apia
Apparatus Meinesz, purchased in Holland Apparatus used in surface vessel really successful only in harbors. Verifies conclusions of Meinesz about use on surface vessels after experiments in 1924, 1925, and 1929

8 1930, Aug 2–Sept 5 Russian Navy Stations 31
Sorokin, Reference 14
Black Sea
Apparatus Fechner 4 pendulum, with photographic recording and modified optical system to give 2 fictitious pendulums as in the Meinesz apparatus Invar pendulums used with the statement that magnetic fields were found to be less variable inside the submarine than on land

9 1931 Italy *Vettor Pisani* Stations 100
Cassinis and DePisa, Reference 15
Mediterranean
Apparatus· Meinesz, borrowed from Holland

10 1931, Aug 18–Sept. 8 *Nautilus* Expedition Stations 7
Villinger Reference 16
Arctic Ocean
Apparatus Meinesz, purchased from Holland.

11. 1932, Feb 7–Mar. 19 United States S-48 Stations 54
Meinesz, Hess, and Brown, Reference 17
Bartlett Deep
Apparatus· Meinesz, with new pendulums constructed in 1931 on the minimum principle

12 1932, July 5–Aug 14 Netherlands O-13 Stations 61
Meinesz, Reference 11, Vol 2, Chapter 2
Mid-Atlantic Ridge near Azores
Apparatus Meinesz, with the pendulums of cruise 11

13 1932, Oct Japan Ro-58 Stations 5
Matuyama, Reference 18
Sagami Bay
Apparatus Meinesz, purchased from Holland

14 1932, Nov 10–1933, Jan 10 France *Fresnel* Stations 30
Marti, Reference 19
Mediterranean, western part
Apparatus Meinesz, borrowed from Holland.

15 1933, Oct 17-Nov. 8 Russian Navy Stations 38
Sorokin, Reference 14
Black Sea
Apparatus same as cruise 8

16 1934, Nov 14–1935, July 11 Netherlands K XVIII Stations 230
Meinesz, Reference 20
Holland to Brazil to Cape Town to Australia to Java
Apparatus Meinesz

17. 1934, Oct. 17–Nov 1 Japan Ro-57 Stations 25
Matuyama, Reference 18
Japan Deep, middle part
Apparatus: same as for cruise 13.

18. 1935, July and August Italy *Des Geneys* Stations 47
Cassinis; Reference 21

Mediterranean, Western part
Apparatus Meinesz, purchased from Holland Boat steered in the meridian during all measurements to avoid Eotvos correction

19 1935, Oct 12-Oct 29 Japan I-24 Stations 29
Matuyama, Reference 22
Japan Deep, southern part
Apparatus Meinesz as in cruise 13

20 1936, Nov 29-1937, Jan 14 United States *Barracuda* Stations 57
Ewing, Hoskinson, and Hess, Reference 23
Panama through Lesser Antilles to Philadelphia
Apparatus Meinesz apparatus used in cruise 10 Crystal controlled chronometer used, placing time reference marks directly on record without use of light valve Half second interval between eclipses to avoid necessity for finding axis of recorded pendulum curve Period and phase readable over entire record

21 1937, Jan 11-Mar 16 Netherlands O-16 Stations 93
Meinesz, Reference 24
Holland to Washington to Lisbon
Apparatus Meinesz, three chronometers, two recording on the pendulum record and all three intercompared by a small recording apparatus before and after each gravity measurement

IV Modification of Meinesz Apparatus by Later Workers

Tsuboi (25) has described a new device for damping free vibrations of the pendulum case in the gimbal suspension.

On the cruise of the U S Submarine *Barracuda* in 1936 (23) an alteration of the method of timing the pendulums was introduced A crystal-controlled oscillator supplying alternating current of constant frequency was used to drive a small synchronous motor, which served as a chronometer. This chronometer, which was constructed by the Bell Telephone Laboratories under the supervision of Mr W A. Marrison, possessed a rate so constant that uncertainty in gravity results caused by fluctuations in chronometer rate were entirely negligible

This motor was mounted in the light box of the Meinesz apparatus It contained a gear, turning at 2 revolutions per second, which produced a momentary eclipse of the light beam on each revolution Thus there were no light valves, which conceivably introduce slightly variable lags, interposed between the chronometer and the recorded time reference marks The chronometers used in all previous work had likewise produced two eclipses per second, but the two parts into which each second was divided were not rigorously equal Therefore one set of the signals had to be disregarded in determining coincidences between the chronometer and the fictitious pendulums, and coincidences were measured on the pendulum record by the intersection of the line of eclipse marks with the axis of the sine curve for the fictitious pendulum The crystal chronometer gave eclipses rigorously one half second apart, and coincidences were measured by the intersection of the ascending and descending lines of eclipse marks, increasing the accuracy and decreasing the effort required for making the measurement

One of the light valves of the standard Meinesz system was retained in the *Barracuda* measurements It was connected to an ordinary chronometer which caused it to eclipse the light for one half second in each alternate second These long eclipses were not used in measuring the periods because of the inferior constancy of rate of the ordinary chronometer They were used to make visible the phase relationship between the fictitious pendulums and the middle pendulum, and as they occurred only in alternate seconds they did not interfere with measurements of the coincidences. For the entire duration of the observation the paper was moved through the light box at the high speed which had been used only at the beginning and at the end of the observing period in all earlier work. Thus both the coincidences and the phase relationships could be measured for any instant during the entire observation Several times daily the crystal chronometer was compared with radio time signals from station NAA by use of an apparatus * which produced a momentary flash of light at the beginning of each time signal The gear of the synchronous motor mentioned above, which was graduated in intervals of 0 01 sec , was viewed in the light from the Strobotac. The comparison with the time signal could easily be carried out with a probable error of 0 002 sec

V SECOND ORDER DISTURBANCE TERMS

In a recent paper of great importance for marine gravity measurements, Browne (26) pointed out the necessity for making a correction, involving second order terms for disturbances caused by motions of the ship, which had been overlooked by all previous workers The principal disturbances for which this correction is needed when the observations are made on a submerged submarine seem to be those caused by the very long waves or swells These swells have periods several times longer than the periods of the gravity pendulums and their effect is readily apparent on the pendulum records, where it produces slow fluctuations in the line of eclipse marks. The procedure previously used corrects only for the first order effect of these accelerations

Let $\ddot{x}$ represent the acceleration of the apparatus in the vertical direction, and $\ddot{y}$ and $\ddot{z}$ the horizontal accelerations perpendicular to the axis of the ship and parallel to it, respectively Then the second order disturbance is given by

$$g = -\overline{\ddot{x}^2}/4g + \overline{\ddot{y}^2}/2g + \overline{\ddot{z}^2}/2g,$$

where the dashes indicate values over the entire duration of the observation. Vertical accelerations cause the observed values of gravity to be too small and horizontal accelerations cause them to be too large Consideration of the shape of a

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* Manufactured by the General Radio Co , Cambridge, Mass , under the name Strobotac

ship indicates at once that the accelerations $\ddot{z}$ parallel to the ships axis will probably be very small The vertical accelerations may be read directly from the pendulum record as stated above The horizontal accelerations perpendicular to the axis of the ship are probably of the same order of magnitude as the vertical accelerations when the course of the ship is perpendicular to the direction of travel of the swells, and is probably negligibly small when the course is parallel to this direction

Meinesz (27) has already undertaken an investigation of the accelerations in a submerged submarine for the two-fold purpose of learning how best to apply the correction to the observations which have already been made, and for testing a device which he proposes to add to the pendulum apparatus to record the necessary data for making the correction in all future measurements He gives a preliminary estimate of the importance of the correction for the older work, stating that it will amount to less than a milligal on very many stations, particularly for those located in enclosed seas where large swells are less common than in the open ocean. This result is confirmed by the records of the *Barracuda* cruise, where vertical accelerations were found to be almost imperceptible in the Caribbean, but definitely present for stations in the Atlantic Meinesz finds that in extreme cases, such as were encountered by him in the Netherlands 0–16 while crossing the Atlantic in 1937 with exceptionally rough weather, the correction may reach 30 milligals for the vertical accelerations alone The correction for horizontal accelerations y will be opposite in sign and, under the opinion stated earlier in this section, will range in magnitude from zero to about twice the value of the correction for vertical accelerations depending on the relation of the course of the ship to the course of the swells For almost all of the *Barracuda* stations the course of the ship was parallel to the direction of propagation of the swells, so it may be expected that the second order corrections will lead to values for gravity slightly greater than those given in the preliminary report (23).

VI NEGATIVE GRAVITY ANOMALIES—MEINESZ BELTS

As is well known, the gravity anomaly at a station is the excess of the measured value of gravity over the theoretical value given by a standard formula We may consider that the formula was selected to make the anomalies come out as small as possible If the theoretical value of gravity has been corrected for topography and for isostatic compensation of the topographic features before comparison with the observed value, the anomaly is called an isostatic anomaly Isostatic anomalies are interpreted to mean that there exists, near the station, an excess of mass over that assumed for isostatic compensation of the topographic features, while negative anomalies indicate a deficiency of mass

A great narrow belt of large negative gravity anomalies, which might well be called a Meinesz belt in honor of its discoverer, was found in the East Indies and elaborately mapped by Meinesz in the years 1926–1929 It is a curved zone over 5000 miles long and usually not more than 60 miles wide, which winds through the entire East Indian island arc as shown in figure 2 It is almost continuous throughout its entire length, and on almost any section across it the negative gravity attains an extreme value of 100 to 200 milligals The belt of negative anomalies shows a close relationship to the tectonic features of the region, coinciding almost exactly with the belt of earthquake epicenters where many earthquakes of the strongest type occur. The volcano belts lie on curves on the concave side of the belt of negative anomalies at a distance of about 100 miles Without exception the typical deep sea troughs of the region are parallel to the Meinesz belt, lying near to it on its convex side.

A second Meinesz belt has been mapped in the West Indies, extending from Cuba around the island arc to Trinidad, as shown in figure 3 This belt was discovered by Meinesz in 1926, and was further studied during the cruises of the U S Submarines S-21, S-48, and *Barracuda* It is similar in all major respects to the belt in the East Indies

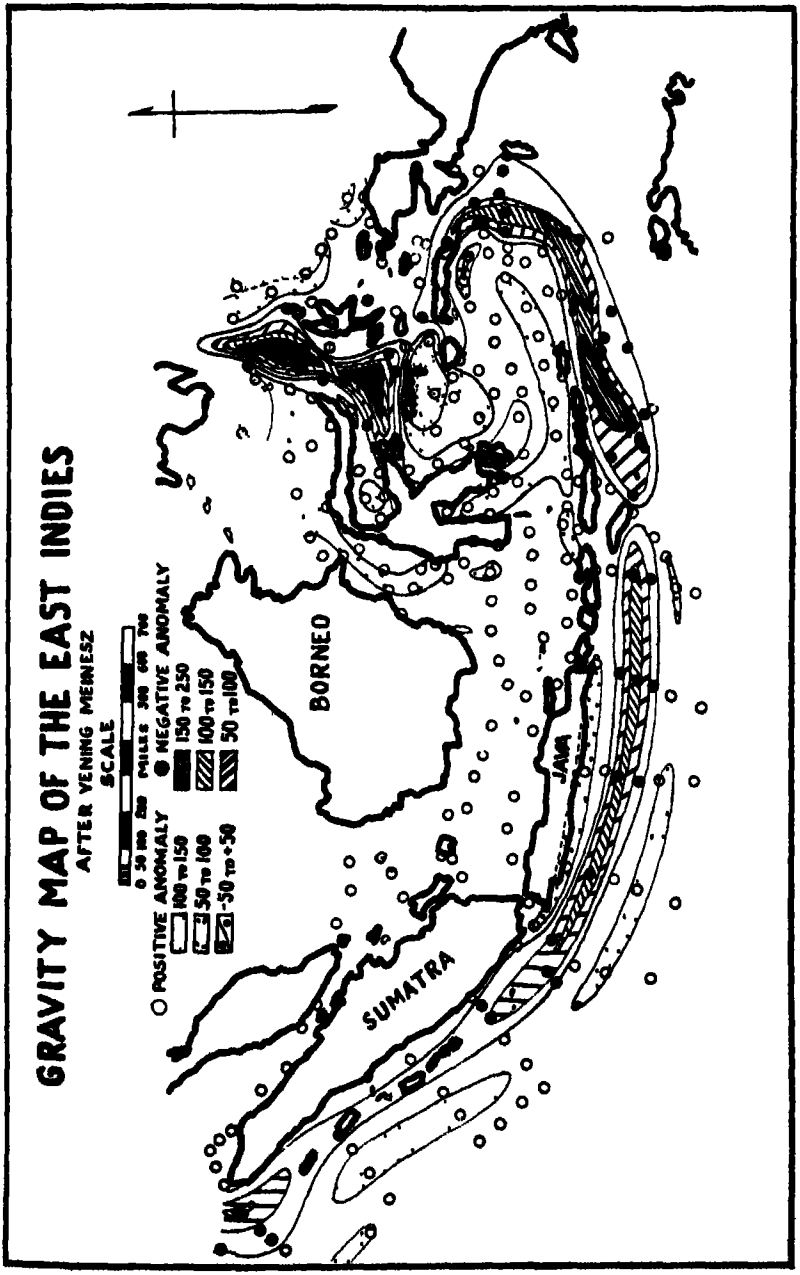

FIG 2 The gravity anomalies in the East Indies

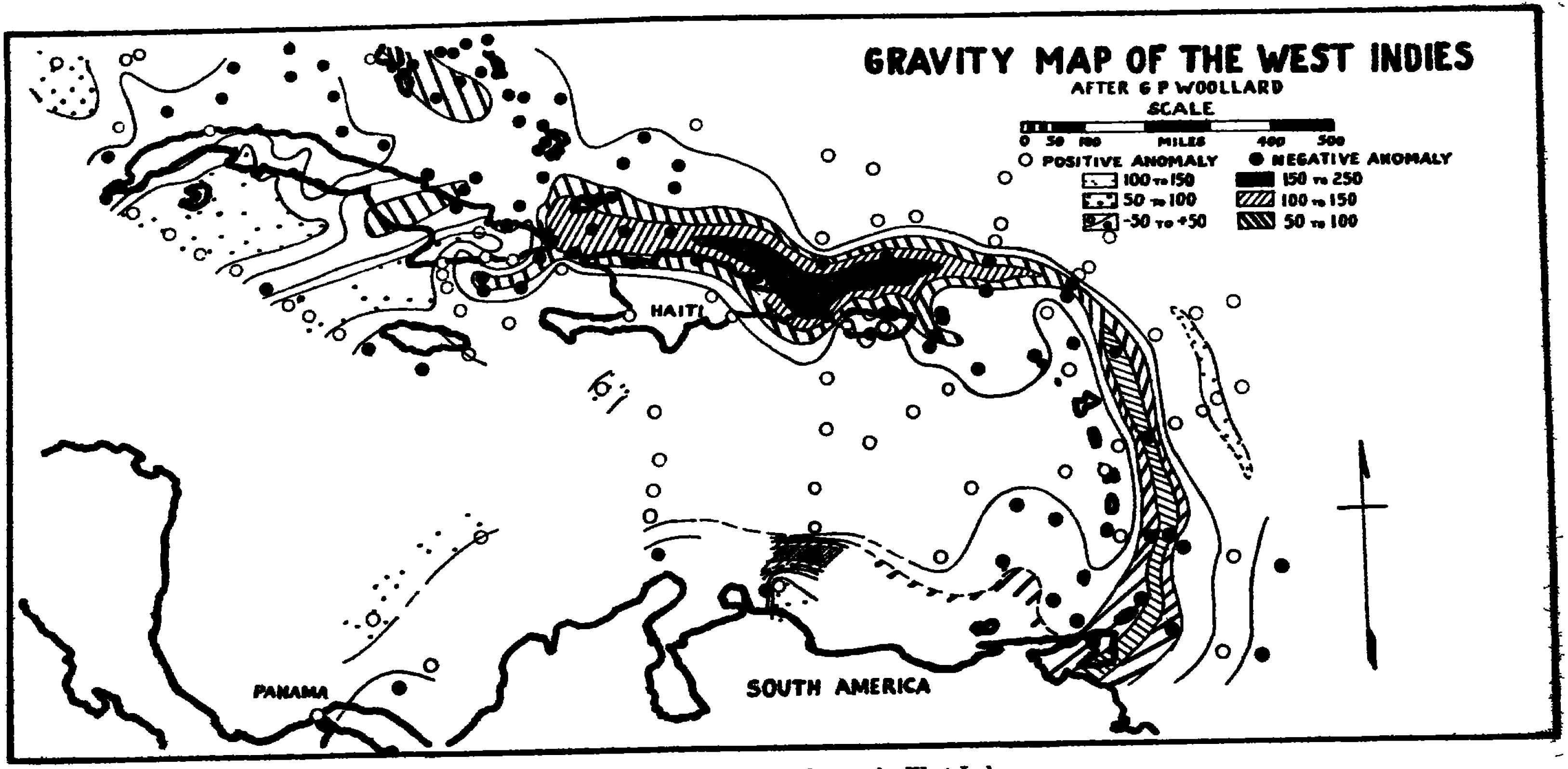

Fig 3 The gravity anomalies in the West Indies

A third belt has been found associated with the Nippon Trench as shown in figure 4 It has been surveyed by the Japanese expeditions between 1932 and 1935 for a length of about 900 miles This belt also resembles the East Indian one in its major features

These narrow belts of strong negative gravity anomalies are probably the most striking features of the gravitational field of the earth which have yet been discovered The close relation which they show to tectonic phenomena indicates that they will give much information about the structure of the crust of the earth and about the processes of mountain building The actual values obtained for the anomalies of gravity in these regions are largely independent of the system of isostatic reduction chosen for arriving at the isostatic anomalies, which proves that the results may not be attributed to an incorrect assumption about the distribution of compensating masses. The explanation advanced by Meinesz is the "buckling hypothesis," which postulates a downward protuberance of crustal material into the denser substratum This is considered as the result of buckling of the crust under compressional stresses The light crustal material is prevented from rising upward and attaining isostatic equilibrium by the continued action of the compressional stresses Taking the density of the crust to be 0 6 gm /cm ^{3} less than that of the substratum and the crustal thickness to be 25 km , Meinesz concludes that a crustal shortening of 50 km will suffice to produce the observed gravity anomalies in the East Indies For a complete discussion of the question, the reader may consult the works of Meinesz and his colleagues (11, 28) and Hess (17, 29)

It now seems probable that every "island arc" has an associated Meinesz belt of negative gravity anomalies, and it is important that additional surveys of island arcs should be made.

VII. Positive Anomalies Over the Oceans

In general positive anomalies of gravity are found over the oceans These are much smaller than the negative

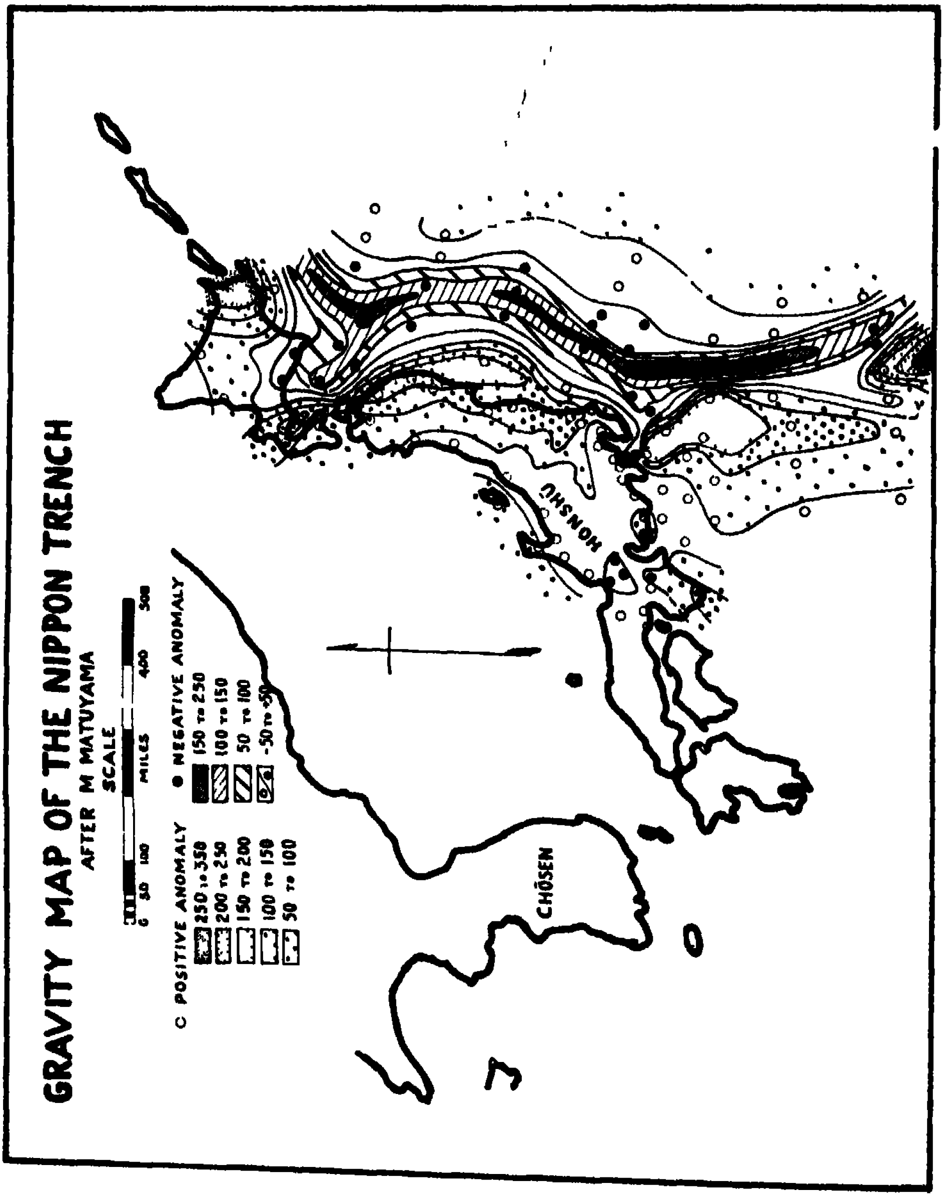

Fig 4 The gravity anomalies over the Nippon Trench

anomalies described in the last section, averaging about 22 milligals in the Pacific Ocean and about 41 milligals in the Atlantic Meinesz has offered the explanation that convection currents in the substratum, upward under the continents and downward under the oceans, produce these large fields of positive anomalies To explain them in terms of compressional forces in the crust would require such great stresses in the crust that this alternative explanation is rejected Hales (30) and Pekeris (31) have published calculations showing the possibility of quantitative explanation of the oceanic anomalies by thermal convection currents in the substratum

It is conceivable that the second order corrections introduced by Browne will remove these positive anomalies over the oceans, but it seems more probable from the discussion of Section V that the correction will eventually prove to be in the opposite direction Dr Bullard reports that preliminary measurements by Browne indicate approximate equality of horizontal and vertical accelerations in deep water

VIII STATIC GRAVITY METERS FOR MARINE MEASUREMENTS

As was mentioned in the introduction, all attempts to measure gravity at sea prior to the work of Meinesz were made with static gravity meters, or gravimeters, instead of pendulums. With the vast improvements which have been made in gravimeters, largely by those using them in prospecting for oil, it is natural that further attempts to adapt these instruments to marine measurements should be made Norgaard (31) has described a static gravimeter, reading to 1 or 2 milligals on land, with which he made tests at sea on a surface ship in the Baltic Sea in 1932 and 1933 His instrument is in principle a modified Cartesian Diver floating in oil, and provided with temperature compensation It did not work very well in a rough sea, but there is a good chance it would be useful for observing in a submerged submarine

Haalck (32) made gravity measurements in 1934 on ships on the Elbe and on a voyage on a surface vessel from Hamburg through the North Sea and the Baltic Sea to Finland and return. He was able to make measurements in the sheltered parts of the route but was not successful in the open sea. His instrument is constructed on the barometer principle, and has certain points of resemblance to one of the instruments built by Siemens It was developed to make measurements on land with a probable error of 2 or 3 milligals His successful measurements in protected bodies of water give him confidence that the instrument can be made to give satisfactory results on a surface ship on the open ocean. The recent work on second order effects discussed in Section V proves that measurements on surface ships will be even more difficult than was previously supposed, but it seems likely that Haalck's instrument would function properly in a submerged submarine

An outstanding difficulty for all static gravimeters for marine measurements is that they do not as a rule enjoy freedom from shifting of the zero-point to the extent that pendulum instruments do Therefore static gravimeters need to be returned to a base station at frequent intervals, which is a much more serious problem for marine than for land work It was originally planned to use a static gravimeter in conjunction with the Meinesz apparatus on the cruise of the *Barracuda*, but this plan could not be carried through

IX GRAVITY MEASUREMENTS IN POLAR REGIONS

While the *Fram* was frozen in the ice and drifting in the Arctic Ocean from 1893 to 1896, pendulum observations were made in the ship and also on the ice near the ship by Scott-Hansen The results have been published by Schiøtz (33) for seven stations A von Sterneck two-pendulum apparatus equipped with a coincidence apparatus was used, but apparently the results are inaccurate due to the effect of tremors in the base on which the apparatus rested

In the voyage of the *Maud*, 1918–1925, Sverdrup (34) made an observation near Cape Chelvuskin with the same apparatus used on the earlier expedition He gives the mean error as 6 milligals

A highly important contribution to marine gravity surveys is now being made by the floating expedition of the U S S R under the leadership of I D Papinin. Four men were landed on the ice at the North Pole by means of an airplane on May 21, 1937, and a camp was established for them On February 5, 1938, the camp had drifted more than 1100 miles, and was near the coast of Greenland at north latitude 74° and west longitude 16°. The party was in danger because the ice floe was breaking up, and rescue parties were attempting to reach them As part of an extensive scientific program, 13 gravity expeditions had been made at the time of the latest report (35) It is probable that these observations were made with an apparatus embodying the principle of the Meinesz fictitious pendulum, as described by Sorokin (14) in the report of his excellent work in the Black Sea, in which case the gravity results will not be prejudiced by tremors in the ice This work is valuable for it promises gravity data in a region where observations are badly needed, and it introduces a feasible method which can eventually give gravity surveys over the entire extent of the polar seas

The possibility of using modern airplanes to move an expedition from station to station on a polar ice sheet has placed a comprehensive survey of the polar seas within our reach, just as the development of submarines capable of making long ocean voyages made possible gravity surveys of the other parts of the oceans

X RELATION TO ISOSTASY AND THE FIGURE OF THE EARTH

The results of the marine gravity measurements have provided a direct confirmation of the principle of isostasy The mass-defect in the deep oceans, represented by the difference in mass between the water and an equal volume of rock, would produce negative anomalies as great as 500 milligals if not compensated by a corresponding mass-excess beneath the floor of the ocean. The observed anomalies are in general positive, and average only one tenth to one twentieth of this magnitude The large deviations from isostatic equilibrium which exist in the Meinesz belts may be considered as very exceptional features to be explained by stresses in the crust

The results contradict the elliptical form of the equator deduced from continental gravity measurements by some geodesists, and favor a gravity formula which does not contain a longitude term

Stokes (36) gave a theorem by means of which the form of the geoid may be deduced from gravity measurements, but in order to apply this theorem it is necessary to have a certain minimum density of gravity stations over the entire surface of the earth Hunter (37) has recently made a thorough study of the number and distribution of stations needed for the application of the theorem of Stokes, and of the precision attainable in computing the distance of the geoid from the spheroid of reference at a given point He concludes that a basic network of 1654 stations distributed uniformly over the surface of the earth would make it possible to carry through the computation with a probable error of ± 10 4 meters, while the addition of 84 suitably located local stations would reduce the probable error to ± 7 0 meters at a given point

It is important that future gravity expeditions shall be planned with the need for this basic network in mind, and marine measurements are particularly important in this connection because many of the areas in which stations are needed are at sea

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GRAVITY ANOMALIES AND ISLAND ARC STRUCTURE WITH PARTICULAR REFERENCE TO THE WEST INDIES

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MEINESZ's discovery of huge negative anomalies in the vicinity of island arcs is probably the most important contribution to knowledge of the nature of mountain building made in this century In the space of this short paper a complete review cannot be made of his findings and of their interpretation, but the references given below will serve to direct the reader if he is inclined to go into the subject (1 to 8). When the significance of the huge anomalies and the structures which they indicate become appreciated, a radical change in some of our ideas on mechanics and processes of mountain building becomes necessary Instead of pure speculation as to what happens in depth during deformation, certain concrete facts may now be substituted which definitely limit and control speculation to great advantage

This symposium on geophysics and ocean basins consists of a group of papers dealing largely with new technique and apparatus for attacking geologic problems at sea, but this particular article is included as an example of the interpretation of data obtained from sonic soundings and gravity measurements Specifically it deals first with general principles, and second, with structure and gravity anomalies in the West Indies The data collected by four expeditions are made use of, these being the investigations of the Netherlands submarine K XIII by Meinesz (1926), U. S Submarine S-21 by Meinesz and F. E. Wright (1928), U S. Submarine S-48 by Meinesz, Hess, and T T. Brown (1932), and U S. Submarine *Barracuda* by M. Ewing, Hess, and A. J. Hoskinson

PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY,
VOL 79, NO 1, APRIL, 1938

(1937) A reasonably close gravity net is now available for the whole of the West Indian region, including a large number of land stations taken by the U S Coast and Geodetic Survey in the northern portion of the area Through the invaluable cooperation of the Hydrographic Office of the U S Navy, many new sounding lines have been made recently in the Caribbean Sea Much credit is due R M Field, whose keen foresight recognized from the beginning the immense importance of Meinesz's work at sea in relation to fundamental problems in structural geology, and through whose efforts the last two expeditions mentioned above were made possible *

FACTS CONCERNING ANOMALIES

1 *Distribution of Anomalies with Respect to Topography*

In most cases the strongly negative anomaly belt lies on the outer (convex) side of the main arc Such is the case southwest of Java and Sumatra and southeast from Haiti around the Lesser Antilles to Trinidad It may lie approximately over the axis of a long narrow ocean deep, as it does for example north of Puerto Rico But most commonly it lies over, or a little to one side of, a ridge which in many cases is flanked by ocean troughs on either side One of these troughs may be a great ocean deep In the case of the Banda arc, where the negative strip lies along a ridge, the inner trough is a great deep, the Weber deep, and in the case south of Java where the anomalies are similarly located, the great deep, Java deep, lies on the outer side of the ridge The ridge may project above sea level to form islands, as it does in the cases of the Banda arc, Timor, Nias, Barbados, Trinidad, and many others

The belt of strongly negative anomalies is bordered on either side by complementary belts of positive anomalies which generally lie on topographic swells (geanticlines), the inner of which commonly emerges above sea level to form the main arc. Examples of an emergent inner geanticline are Hispaniola, Puerto Rico, the Lesser Antilles, Java, and Sumatra. Christmas Island is one of the few examples of an emergent outer geanticline, though Aroe Island, part of New Guinea, and part of eastern Venezuela may also be cited

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* The complete report on the West Indies will be published shortly as the results of the cruise of the U S Submarine *Barracuda* (Navy-Geophysical Union Expedition)

2 *Size of Anomalies*

The maximum negative anomalies observed are over 200 milligals, and anomalies of 150 milligals are common No anomalies of comparable size (regardless of sign) are known on the continents

3 *Width and Length of Negative Anomaly Strips and Their Distribution*

The width of the negative strip, though variable, averages about 150 km. The strongly negative portion of the strip is commonly less than 50 km wide The negative strip in the East Indies is about 5000 miles long, but with further investigation it seems likely that it can be extended to the Marianne islands, continuing to east of Japan where the strip has been located, and thence northward to and along the Aleutians, making it very many times longer A negative strip might be predicted to occur associated with the New Guinea-New Zealand arc, and another will almost certainly be present around the Cape Horn, South Georgia-Antarctica island arc Details of the negative strip in the West Indian arc will be dealt with in this paper Indications of a negative strip in the Mediterranean from the Gulf of Taranto and southwestward on the Alpine trend have been found and a similar belt perhaps may be found on the Himalayan trend along the north shore of the Arabian Sea. (It seems likely that negative strips will be found only in the arcs mentioned above and nowhere else)

In no case are two parallel strongly negative strips known, but in every case it appears that the negative strip is a single continuous band.

4 *Location of Volcanoes with Respect to the Negative Anomaly Strip*

Volcanoes lie on the concave side of the negative strip and about 160 km away from the axis of strip They are probably located on radial fractures roughly perpendicular to the negative strip Groups of two or three volcanic centers, one behind the other along radial lines, may be noted on Java for example

5. *Serpentinized Peridotite Intrusions and the Anomaly Belt*

Serpentinized peridotite intrusions occur along or very close to the negative strip, cutting rocks older than the first great deformation, which deformation was probably responsible for the first development of the negative strip They seem to be intruded during the deformation

EXPLANATION OF THE NEGATIVE ANOMALY STRIP

The anomalies of the negative strip are so large and of such a local nature that many of the explanations possible for small or regional anomalies can be eliminated Thus the sum of the errors which may be introduced by observational inaccuracies, imperfections in topographic corrections and gravity formulæ, or incorrect assumptions as to the type of isostatic compensation, cannot make up more than a small fraction of such anomalies as these There can be no doubt that the major portion of the anomalies present in the negative strip is due to an abnormal mass distribution in the Earth's crust below the strip, and probably to local departure from isostatic equilibrium

Meinesz's explanation for the anomalies of the negative strip is that the Earth's crust buckles downward in a huge vertical isoclinal fold, and thus the light material of the upper crust might extend downward to a depth of 40 to 60 km. This would be sufficient to give the observed anomalies if the lower portion of the downbuckle had a specific gravity deficiency of about 0 3. No other adequate explanation has yet been advanced (Fig 1)

Application of the theory to the West Indian region results in the coordination of many geologic facts previously merely a collection of observations with no apparent relationship to one another So successful is the Meinesz theory in the West Indies, both in predicting relationships which are to be expected (and have since in a number of cases been found) and in joining together in a single structural entity observations which formerly fit into no definite pattern, that the writer has become completely convinced of the soundness of the theory in general, though in detail it may need some modification He believes, as Meinesz originally postulated, that only the upper 25 km of the crust buckles, and the material beneath that deforms by flowage laterally This idea is a corollary of the writer's concept of the formation and intrusion of peridotites in the region of the tectogene (23) * It seems very likely that the crust becomes gradually weaker with depth as temperature increases, until finally a zone of practically no strength is reached at the base of the crust.

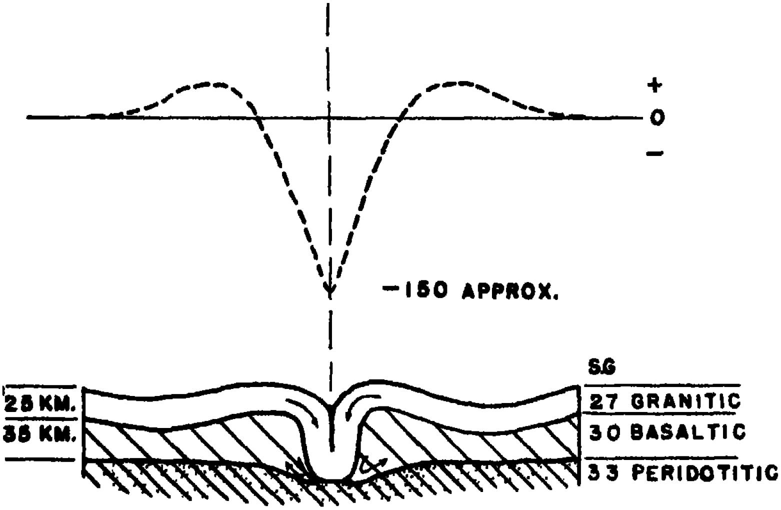

FIG 1 Crustal buckle, specific gravity distribution and resultant anomaly curve

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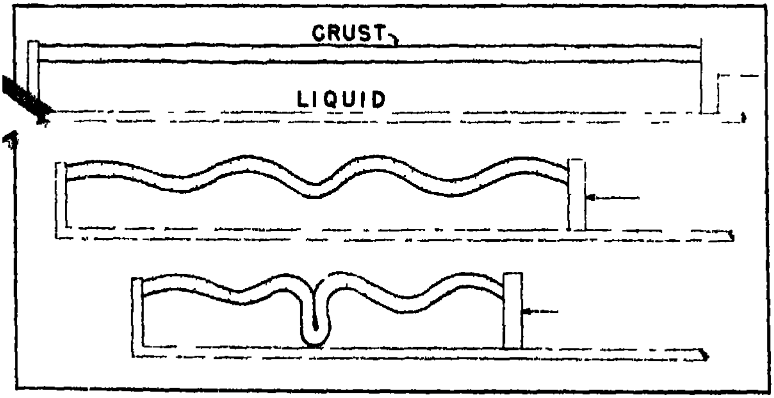
* Tectogene = crustal downbuckle, Kuenen (2)

Thus while the upper part of the crust may have sufficient strength to be buckled downward, the lower part would certainly have less strength and might reasonably be considered to deform by flowage Inasmuch as the anomalies indicate a disturbing factor about 50 km wide, the division between crust which has buckled and crust which has flowed may well be placed at 25 km depth (the 50 km width consists of the two limbs of the isoclinal downfold each 25 km. thick).

KUENEN'S EXPERIMENTS

Kuenen's (2) analytical examination and experimental test of Meinesz's theory offers strong support The experiments performed by Kuenen are of particular validity because two factors have been taken into consideration which are commonly neglected in experimentation with geologic models. The first is that the strength of materials used has been chosen so as to be of the right order of magnitude for the scale of the model, and second, the crust of the model has been floated on liquid paraffin to supply the zone of no strength beneath the crust



KUENEN'S EXPERIMENTS
FIG 2

The experiments resulted in, first, the bending of the crust of the model into a regular series of sine curve folds, and finally into the buckling downwards of one syncline (Fig. 2).

(Two adjacent synclines buckled downward in a few ex; its ments, and then moved together and coalesced into a double structure No analogy to this has been found in island arcs) In no case does an anticline buckle upwards Once a syncline has buckled, further compression merely deepens that syncline, the "crust" coming up to that syncline and then running downwards over "rolling hinges "

In another set of experiments, Kuenen covered the crust with a very weak layer to represent a cover of sediments In the first stages of deformation, the sediments are carried along on the competent crust, but when the crust downbuckles, the weak sediments are squeezed out of the core of the tectogene like toothpaste out of a tube, forming alpine types of structure (Figs 3, 4, 5) As will be seen later, structures of this upsqueezed type are found in connection with the negative strip in the West Indies.

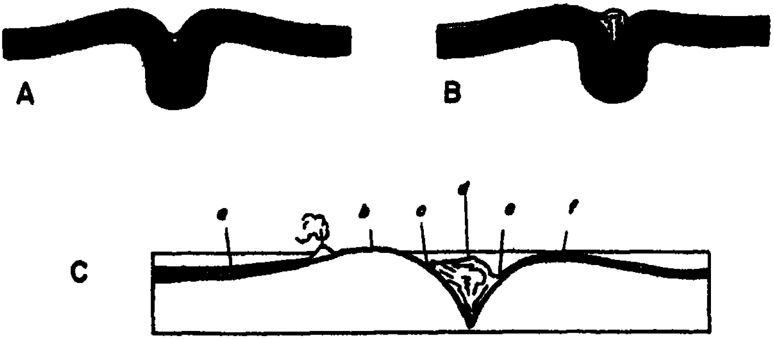


Fig 3 *A* Buckling of the crust with little or no incompetent cover The anomalies lie over an ocean deep *B* Incompetent cover present and weak material is squeezed up in geotectoclinal zone Anomalies lie over a ridge *C* The same in detail *a* = geosyncline, *b* = emergent inner geanticline, *c* = ocean trough of moderate depth, *d* = geotectocline—upsqueezed zone, *e* = great ocean deep, *f* = submerged outer geanticline

THEORETICAL IMPLICATIONS OF THE MOUNTAIN-BUILDING BY DOWNBUCKLING

A further modification of Kuenen's experiments might be considered. In both the East and West Indies, according to

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writer's concept, a second great deformation has occurred a considerable time after the first one, during which the tectogene originally was developed In the interval between the first and second great deformations, one or both of the geanticlines on either side of the tectogene may have emerged above sea level Erosion of these emergent portions, plus a

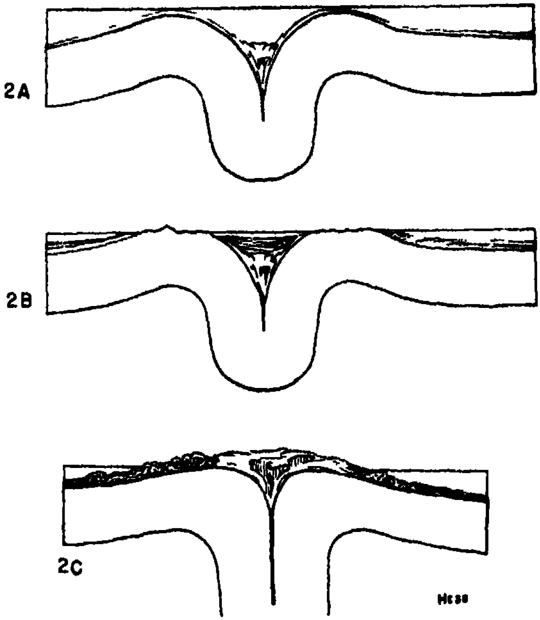

Fig 4 2A similar to B of figure 3 but whole structure here is submerged 2B Structure emerges and erosion and sedimentation take place 2C A second great deformation forces the tectogene down further The old deformed sediments of the original geotectocline are pushed up further and the younger interdeformational sediments are strongly deformed by the jaw crusher effect as the two limbs of the tectogene come in and go down over rolling hinges The younger sediments on the geanticlines are much folded when they come up against the bulwark formed by the geotectocline

great contribution of volcanics from the concave side of the arc, may deposit great thicknesses of material in "geosynclines" within the inner geanticline, and perhaps also outside of an outer geanticline, as well as in the central basin over the tectogene itself This basin over the tectogene will henceforth be called the "geotectocline" because of its different structural behaviour and in many cases its different type of sedimentary sequence than that which occurs in a geosyncline as the term is generally used today * The second deformation will deform very intensely the material of the geotectocline Strong folding and perhaps thrusting of the interdeformational sediments,† if deposited, will occur, and probably further upthrusting of material originally squeezed

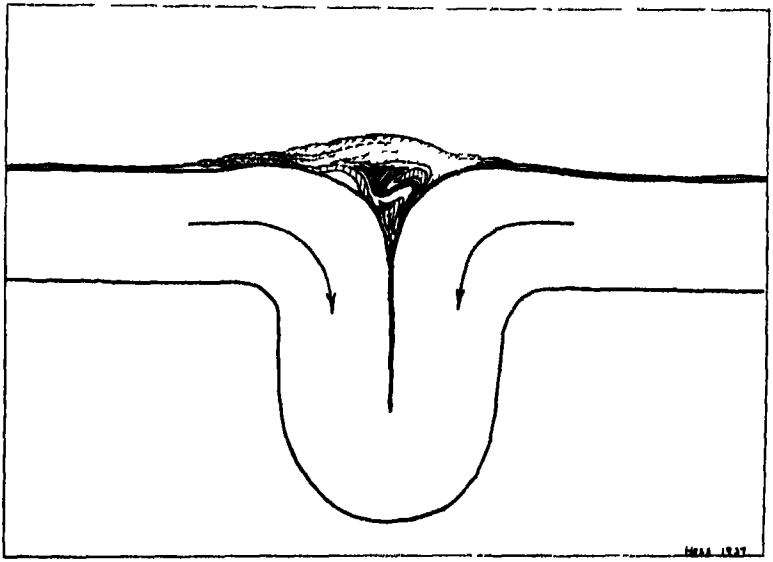

FIG 5 General section of the Alps superimposed on the tectogene Both features drawn to the same scale with no vertical exaggeration

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* I hesitate to introduce a new term, but this one seems necessary unless a long descriptive phrase be written out each time this structural unit is considered The term "geosyncline" itself is difficult to use because it has been defined in several different ways some of which are expressed in terms of hypothetical structural concepts and hypothetical conditions of sedimentation which probably have no actual counterparts in nature In this paper the term geosyncline is used broadly to signify an *elongate gently downwarped trough* of large size (at least tens of miles and perhaps hundreds of miles or more in length) The definition specifically includes no implication as to the manner of its warping Sediments may or may not be contained in it, but, if present, the nature of the sediments is not specified

† Sediments deposited between two periods of deformation

out of the tectogene, if present, will take place This happens because the material in the geotectocline is pinched between a sort of jaw-crusher as the main crust moves toward the tectogene and down over its rolling hinges Furthermore, the material which may be on the geanticlines or in the adjacent geosynclines on the sides (or side) away from the geotectocline will be carried forward toward the geotectocline This material may then impinge against the upsqueezed mass in the geotectocline Upon coming against this bulwark, the weak upper part may be literally scraped off the main crust as it rides forward and down into the tectogene This is particularly true if very incompetent horizons, such as salt beds or argillaceous sediments are contained in it The result will be that the cover will be thrown into folds and perhaps develop a schuppen structure as its forward progress is stopped by the bulwark and the main crust under-rides or in reality underthrusts it The Juras can perhaps be cited as an example of such structure (Figs. 3 and 4)

Though the above is presented as speculation, it was arrived at largely by consideration of known structures in folded mountain systems and built up from generalizations concerning these systems which most geologists would today accept These generalizations were then fitted to the theory of downbuckling The narrow central area of intense deformation and metamorphism so common in intensely folded mountain systems becomes the geotectoclinal zone The broad areas generally characterized by open-folding and in many cases by great thickness of sediments become the adjacent geosynclinal areas This is the tectonic zone in which a large proportion of the world's great oil fields are found Thus in the West Indies the geotectoclinal zone may be seen in the metamorphosed and much deformed sedimentary rocks of the North Range of Trinidad and its continuation in the coast ranges of northeastern Venezuela, and the folded geosynclinal zone of thick sedimentary sequences (younger than the first deformation in large part) may be found to the south in areas now being exploited for oil In the East Indies the geotectoclinal zone is found on Nias, Timor, Tenimber, Ceram, etc , and the folded geosynclinal zone is represented by the great oil field areas of Java, Sumatra, etc (Umbgrove's poly- and idio-geosynclinal areas respectively (1)) *

Let us now turn from general theory and speculation to the more concrete topic of actual relations in the West Indies

The West Indies

Gravity Field (Plate I)

The most significant feature of the gravity field is the well defined negative strip which extends from the eastern end of Cuba completely around the arc to Trinidad where it probably crosses that island, the Gulf of Paria, Northeastern Venezuela just south of the Coast Range, hence northwestward to sea around the north side of the Dutch islands, and finally southward into Colombia The portion between Trinidad and the Dutch islands has not been investigated, but almost certainly the anomalies will be found there Meinesz is probably taking some stations in that area at present in connection with tests he is making

The anomaly values along the axis of the negative strip from Cuba to Trinidad commonly reach − 150 milligals The largest anomaly is − 183 over the Brownson Trough north of Puerto Rico Here and north of Hispaniola the axis of the strip is practically coincident with the axis of the trough Over the sharp flexures in the negative strip, both at the north end of the Lesser Antilles northeast of the Virgin Islands, and at the south end in the vicinity of Trinidad, the anomalies are somewhat smaller, being under − 100 milligals

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* Umbgrove's and Kuenen's analysis of the East Indies (1) have been most helpful in working out the West Indies and served as a solid base from which to begin On the whole our conclusions agree remarkably well, only differing at a few points In dealing with such complex sets of data involving much inference it is surprising and also pleasing that we do agree so well. It is also to be expected that the differences in evidence found in the East and West Indies and differences in viewpoint and attack of the investigators are bound to lead to some divergences of opinion

Perhaps this is due to a lateral stretching of the tectogene where the sharp bends in the strip occur

The Brownson Trough, previously known north of Puerto Rico and the Virgin Islands, curves around parallel to the Lesser Antilles and extends almost as far south as latitude 17° Southward from this latitude a ridge appears along an extension of the same axis. Barbados lies on this ridge, and the negative strip continues along the ridge just as it did along the deep This is interesting when Kuenen's experiments are taken into consideration, for certainly the topography and gravity anomalies north of Puerto Rico strongly suggest the type of structure shown in Fig 3a, whereas a section from the Lesser Antilles through Barbados indicates the structural conditions of Fig. 3c In the East Indies the negative strip generally does not lie over the deep but along a ridge which may be flanked on one or both sides by troughs. Presumably most of the East Indian negative strip corresponds to the Barbados type of structure

From latitude 19° to latitude 15°, the anomaly axis lies to the west of the axis of the deep at the north end, and west of the axis of the ridge at the south end. The anomaly profiles are somewhat asymmetrical, being steeper on the west side of the axis This may mean a slight eastward overturning of the tectogene

The strongly negative strip terminates at the eastern end of Cuba A belt of smaller negative anomalies, however, does continue westward with its axis approximately over the northern half of Cuba. The writer believes it very probable that the negative strip did at one time extend the length of Cuba and thence southwestward to and across Gautemala. The writer will return to a discussion of this point later.

Positive anomalies are found in bands on either side of the negative strip The crests of the positive bands lie about 150 km on either side of the axis of the negative strip, though in a few places they may come as close as 100 km. or as far away as 200 km The positive anomalies of these bands generally range from + 20 to + 40 in the West Indies.

An exceptionally large anomaly is found at Curacoa, however, + 80 The analogous positive anomaly bands in the East Indies generally show much higher values, many being over + 100, although the negative values found in the East Indian negative strip are about the same as those of the West Indies, or a little smaller on the average

Outside of the arc a faint suggestion of small undulations exists parallel to the negative strip, both in gravity field and topography The distance from crest to crest of these undulations seems to be about 250 km.

In the basins of the Caribbean and Gulf of Mexico the anomalies are generally positive. As a rule, the deeper the water for a given basin, the more strongly positive are the anomalies The profile made by the S-48 from Jamaica to the west end of Cuba shows the relationship most clearly Here the anomaly profile drawn to an appropriate scale over the sounding profile results in the one becoming an almost perfect mirror image of the other Enclosed basins in other parts of the world show similar relations The reason for this relationship is not apparent, and no adequate explanation can be offered at present Meinesz's suggestion of downward convection currents below the crust to explain the positive anomalies in the oceans does not seem applicable here, because such a process going on at considerable depth does not seem consistent with the very close correlation of anomalies and topography.

Serpentinized Peridotite Intrusions (Fig 6)

In the East and West Indies, as well as in other island arcs of this type, a belt of serpentinized peridotite is always present in the most intensely deformed zone In the East and West Indies the serpentines may be seen to follow closely the negative strip except where younger sediments and volcanics hide them from view The writer has made a fairly exhaustive study of this particular type of intrusion (21 to 23). The conclusions arrived at are that the serpentinized peridotites of the type found in island arcs and in the

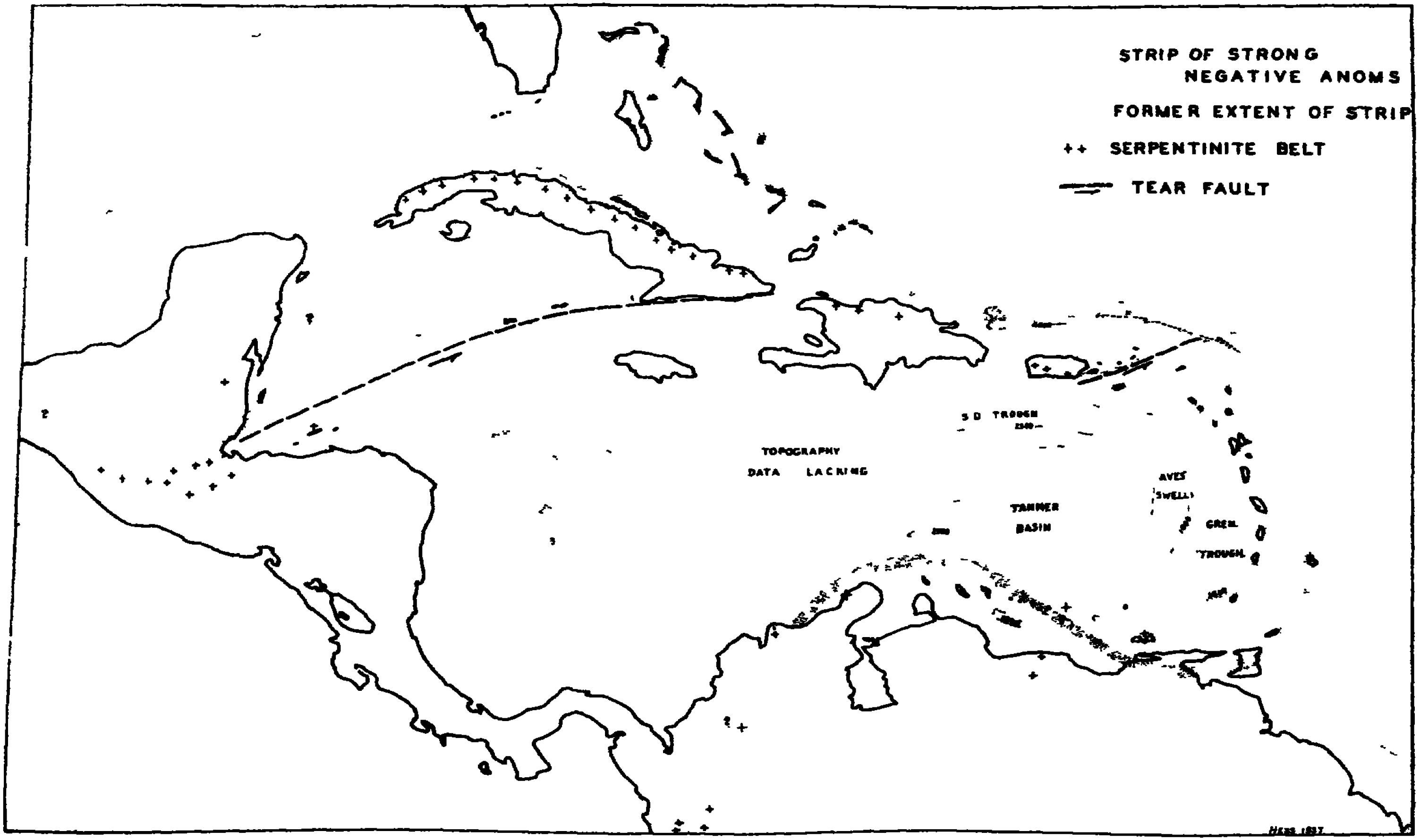
STRIP OF STRONG NEGATIVE ANOMS
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Fig 6

geotectoclinal zone of all mountain systems represent an ultramafic magma which is intruded during the first great deformation when the tectogene is formed Furthermore, they apparently never occur under any other conditions than *in connection with such highly deformed zones* They are extremely useful indicators of the position of the geotectoclinal zone in old, now deeply eroded, mountain systems, and also are most helpful in accurately dating the time of deformation, and extending this dating for the whole length of a given serpentine belt A second deformation, shoving the same tectogene down again, does not seem to produce a second period of intrusion of this magma

In the West Indies a great serpentine belt extends east-west across Guatemala, the whole length of Cuba north of the central axis, through northern Hispaniola, and across Puerto Rico It is not found in the Lesser Antilles, because if it were present it would probably lie a little to the east under water, but if some of the marginal intrusions were present in these islands, they would be covered by the younger sediments and volcanics which are all that outcrop on them The serpentines reappear in the island of Margarita, and are present on Orchila and El Roque, and again at Cape Vela on the Goajira peninsula, hence they apparently bend southward to form the great serpentine belt of the Cordillera Central of Colombia

The serpentines intrude Upper Cretaceous rocks for the most part But in Cuba they are probably younger than certain Lower Eocene beds, and definitely older than the Upper Eocene on that island There is much evidence of intrusion during deformation The most probable date of intrusion for the whole belt is approximately at the end of Middle Eocene

These intrusions may be made use of in two connections in the West Indies. First, they indicate the position of the negative strip in the unsurveyed stretch between Trinidad and the station north of Bonaire where the strip was again picked up Second, they clearly show that the negative strip once continued along the north coast of Cuba, and thence to Guatemala and westward, but it has since largely disappeared They also show that the negative strip in the southern Caribbean joins with the Cordillera Central and once extended down along it, though today it has probably disappeared just as is the case in Cuba

AGE OF THE NEGATIVE STRIP

Though many geologists who have not worked in the West Indies have a tendency when writing about that area to place a great deformation at the end of the Cretaceous, there is fair agreement among those who have studied the region in recent years that the great deformation came within the Tertiary It apparently should be placed before the widespread Upper Eocene deposits and after certain Lower and Middle Eocene sediments The end of Cretaceous was in many places marked by emergence, so that a disconformity may be present between it and the Eocene, but so far as the author is aware, no folding occurs at this time in the West Indies.

The most intense zone of deformation of earliest Tertiary and Cretaceous rocks follows the present negative strip (and its former extensions as suggested above) Portions of the same zone were strongly deformed again in late Miocene and Pliocene time* The serpentines, as has been mentioned, accompany only the Eocene deformation The conclusion is that the negative strip was formed during the Eocene deformation, but has been rejuvenated to some extent by further shoving down of the tectogene during the late Tertiary deformation

GREAT FAULTS OF THE WEST INDIES AND THEIR RELATION TO THE ANOMALIES

The greatest fault in the West Indian area is that which lies along the northern scarp of the Bartlett Trough from

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* Another deformation about middle Oligocene in age may be noted in Haiti and northern South America

Guatemala to the Windward passage, and bounds the southern coast of eastern Cuba This fault is still active today, but some consider it a feature which has been active since great antiquity With this the writer cannot agree He believes it was formed during the late Miocene deformation Hill (13) says that the conglomerates of the Richmond beds (early Eocene) in Jamaica indicate land at that time to the northeast (now the eastern part of the trough) The now isolated islands on the borders of the trough, Swan Island and the Caymans, have Tertiary limestones containing such terrigenous material as quartz and mica. Furthermore, it is not likely that the flat-lying Oligocene and Miocene limestones of the Caymans, which have in part been correlated with Jamaica, were laid down at the very brink of a great fault trough which now separates Jamaica from those islands

The writer believes that the fault along the north side of the Bartlett Trough is one along which horizontal movement took place during the later Tertiary deformation The south side moved east, the area south of the fault was thus relieved of compression and became complexly block faulted The area north of the fault, Cuba, suffered only a moderate amount of late Tertiary deformation, whereas Haiti, which was not so relieved, became very intensely folded in Miocene and Pliocene time This is the cause of the chief difference in the late Tertiary geologic histories of Cuba and Haiti Also it explains the abrupt disappearance of the negative strip at the east end of Cuba and its present absence from the whole length of Cuba Presumably movement along the fault took up the stress of the late Tertiary deformation, so that the tectogene was not rejuvenated north of the fault and actually pressure has been so much relieved that the tectogene under Cuba has largely disappeared by lateral spreading, isostatic uplift, or both

A smaller fault on the north side of Anegada passage, south of the Virgin Islands, which probably is of the same type, has had a similar though less striking effect on the area to the north of it The late Tertiary rocks of Puerto Rico, according to Myerhoff, are but slightly deformed The diminished values of the negative anomalies of the strip north of the Virgin Islands may also be an effect of the Anegada fault, though the writer has suggested an alternative explanation above

An east-west fault is suggested by the topography just north of Barbuda

On the east side of the negative strip a great fault scarp 6,000 feet high (south side up) was located by sonic soundings east of Guadeloupe near longitude 57° This apparently also extends east-west

A number of east-west faults were mapped by H Hanna on the island of Barbados

Great faults probably bound the block of metamorphosed rocks comprising the north range of Trinidad and its extension into northeastern Venezuela according to Kugler These ranges may represent up-squeezed blocks of metamorphosed Cretaceous sediments in the geotectoclinal zone

All of these faults, except the last mentioned, run up to and probably terminate in the geotectoclinal zone It seems to the speaker they were formed by adjustments of the crust as it moved up to the tectogene and down into it. Relative differential horizontal movements of one sector as compared to an adjacent one would be expected to take place as the crustal downfold formed Most of these adjustments, which are now discernible, seem to be related to the second great deformation

If we postulate a downbuckling of the upper crust to a depth of 60 km (or perhaps more if several deformations of the same tectogene take place) along a sinuous curve such as presented by the East or West Indian negative strips, great horizontal adjustments must take place in the crust, both inside and outside of the arcs. Horizontal movements of the order of magnitude of 50 km along such faults as the Bartlett Trough fault are not only likely, but inevitable, if the crust is to adjust itself to a curved downbuckle of this size. Thus it is not inconceivable that Haiti has moved N.N E. 50 km. or more, and once stood below and adjacent to Cuba, or that the portion of the crust now forming the Lesser Antilles geanticline once stood far to the west of its present location, so that it formed a continuous chain with the southeastward trending folds to be found in the Cretaceous rocks of Puerto Rico, which now strike into the Caribbean, where no trace of them is discernible on the sea floor

STRUCTURES OF THE GEOTECTOCLINAL ZONE

The small area of outcrops of older rocks in Barbados presents an extremely interesting picture Barbados lies almost on the axis of the negative strip and typical geotectoclinal conditions should obtain there The writer offers the following interpretation of the history of Barbados The Oceanic series, probably deep-water sediments, are moderately deformed They lie above the very intensely deformed Scotland series, which are shallow water or perhaps in part terrestrial sediments of quartzose character, no doubt derived from a once emergent geanticline to the west The lower part of the Oceanic series is Upper Eocene in age according to Kugler, and the Scotland series very slightly older Between these two formations is found what has been described as a "mud flow," containing huge blocks of sandstone in a silty matrix But to the writer this breccia bears a strong resemblance to the outcrops of the great submarine landslide which he has seen in the city of Quebec (see Collet, Bailey, and Field, 14) Furthermore, since they lie on the junction between shallow water or terrestrial sediments below and deep sea sediments above, with practically no time interval between them, this hypothesis becomes even more likely. The following sequence of events is tentatively suggested In the interval of time between the deposition of the Scotland series and the Oceanics, the great deformation took place forming the tectogene The Scotland series were squeezed up out of the core of the tectogene and thus intensely deformed, but the downward movement forming the tectogene left the tops of these folds at the bottom of a deep steep-sided ocean trough. Silt and blocks of the Scotland series rocks slid down the steep sides covering portions of the bottom of the basin This was followed immediately by the beginning of deposition of the deep water sediments—the Oceanics For a long period of time the deposition continued It is not known what the upper age limit of the Oceanics is Sedimentation may have continued into the Miocene In the Miocene deformation the Oceanics were folded and the whole sequence squeezed further up out of the tectogene again, approaching the surface of the sea or actually emerging. Some marine sediments and coral reef formations follow, accompanied by further uplift, possibly as a result of isostatic adjustment. Today the island emerges from the sea to a height of 1,100 feet and the coral reef cover has been stripped off the northeastern portion

In general thrust faulting and overturning of anticlines occurs in both directions outward from the axis of the geotectoclinal zone In most cases thrusting and overturning is much more extensive on one side of the axis than on the other (the Alps, for example) In northeastern Venezuela the folding becomes much more intense, proceeding from south to north toward the Coast Range, and as that range is approached thrust faults with southward displacement may be found (see Hedberg and Kamen Kaye, 15, 16) In Trinidad south of the North Range, overturning and thrust faulting is dominantly southward In the metamorphosed sediments of the North Range itself, the overturning is in the opposite direction toward the north, and small thrust faults with northward displacement may be seen in these rocks Very close to the south side of the North Range, late Tertiary sediments may be observed dipping in toward the range. The junction between the late Tertiary sediments and Cretaceous metamorphics of the North Range here must be a steep fault It appears that the rocks of the North Range have been thrust steeply upward and represent a slice of rocks from deep in the geotectoclinal zone. This movement may represent an isostatic adjustment since the last deformation (in as much as the range is nearly over the axis of the tectogene), taking place along older steeply dipping fault planes related to the Mio-Pliocene deformation.

Trinidad is also interesting in that it presents a very close resemblance stratigraphically and structurally to Barbados. The Mount Moriah formation, with a great boulder bed and block conglomerate at its base, is equivalent and analogous to the Oceanic series of Barbados with its basal "mud flow" No doubt Trinidad in this epoch has a history much the same as that already outlined for Barbados

Again in Curacoa, on the south side of the geotectoclinal zone, Molengraaf (17) described the folding as decreasing in intensity southward, and the overturning is toward the south

Along the north coast of Cuba the overturning of folds and thrusting seems to be dominantly northward, but on the south coast in Pinar del Rio and probably also in the Trinidad mountains, the thrusting and overturning are in the opposite direction The axis of the geotectoclinal zone runs between the two

VOLCANIC ACTIVITY

Volcanic activity at present is limited to the smoothly curving arc from Saba on the north to Grenada on the south. This arc terminates abruptly a few miles northwest of Saba and a few miles southwest of Grenada This arc does not represent the crest of the inner geanticline The structural crest generally lies thirty or forty miles to the east of it. At the north end of the arc islands, largely made up of sedimentary rocks, occur along the crest, but the southern half of the crest is covered by water.

The volcanic arc is probably underlain by Cretaceous rocks, such as those in the Virgin Islands. Lacroix's (18) description of xenoliths of the basement rocks brought up in the volcanics include gabbros, diorites, diabases, metamorphosed limestones, and cordierite rocks, no doubt metamorphosed equivalents of argillaceous sediments Almost all of the islands, though dominantly made up of volcanic material, do have small amounts of sediments of various ages

At the end of the Cretaceous, volcanic activity was much more extensive, however, and apparently extended for the whole length of the present geotectoclinal zone Thus great masses of volcanic material are present in the late Cretaceous sequence of all the Greater Antilles as well as in those of the Dutch islands north of Venezuela Where erosion has cut deeply enough, quartz diorite and granodiorite intrusives may be exposed, no doubt the intrusive equivalents of the dominantly andesitic volcanics These are of the same type chemically as the great series of Andean intrusions

Sonic soundings show a series of peaks on the western flank of Aves Swell parallel to the Lesser Antilles arc and 250 km west of it Aves Island is the only one which projects above sea level Nothing is known concerning the nature of this rock Profiles across the peaks strongly suggest submerged volcanoes The lack of seismic activity along the greater part of this swell in the vicinity of the peaks suggests that if they are volcanoes they are extinct One peak a few miles northwest of Aves has, however, been the locus of three earthquakes These are the only ones recorded for the whole length of the swell

SEISMIC ACTIVITY

Earthquake shocks of low intensity are very frequent along the Lesser Antilles arc and may be directly correlated for the most part with activities of the volcanoes

In a general way it may be said that there is a correlation between seismic activity and the negative anomaly strip It is not, however, a direct relationship Comparatively few strong earthquakes have their epicenters on the strip. From the Virgin Islands to Barbados, for example, not a single earthquake has been recorded on the strip Again, north of Hispaniola no earthquake epicenters are found on the negative anomaly belt In the southern Caribbean no epicenters lie on the strip for its whole length, from where it probably goes to sea in northeastern Venezuela to Colombia (as Captain Heck points out in the discussion) A strong earthquake, however, did occur a few years ago just where the strip presumably leaves the mainland of Venezuela, striking to the northeast (Cumana earthquake) The only earthquake epicenters recorded on the strip or very close to it occur from Barbados to Trinidad and in the Brownson Trough The only conclusion which the writer can draw from these data is that the tectogene is at present in a rather plastic state and deforms by flowage rather than by the sharp displacements along fractures which would produce earthquakes

Earthquakes are numerous and commonly of major strength along the fault zones and probable fault zones which run into the tectogene In this zone we are dealing with normal crust which, unlike the now heated up crust deeper in the tectogene, reacts to stress in many cases by fracturing It is these readjustments (mostly in the inner, concave side of the arc, but also present on the outer side) caused by differential movements of various sectors of the crust as they move toward the tectogene which apparently produce most of the earthquakes In this sense there is a correlation between seismic activity and the belt of strongly negative anomalies

The Puerto Rico-Virgin Island area close to the Anegada fault is an area of great seismic activity Seven earthquake epicenters are located in the Bartlett Trough, and quite a few more in the immediate vicinity, particularly in Jamaica

The west side of Central America northward into southern Mexico is a region of most intense seismic activity, and in part an area of great volcanic activity. These phenomena, however, do not seem to be related to the major structures of the island arc, but are of more recent origin and probably are to be correlated with a northwesterly trending fault zone diagonal to regional structure

As Captain Heck points out,* the earthquake belt in northern South America departs from the negative anomaly strip and swings westward from Trinidad across Venezuela, and then southward in western Venezuela and eastern Colombia with the Eastern Cordillera of the Andes.

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* See discussion in this symposium

It is interesting to note that the area north of the great Bartlett Trough fault is completely devoid of earthquake epicenters All of Cuba, Florida, and the Bahamas, are free of earthquake epicenters (except for a single center near the eastern margin of the area in the channel north of the eastern end of Cuba) This area seems to be one of unusual quiescence at present The reason is the same as that given for the general lack of strong deformation in Cuba at the time of intense folding in Haiti and elsewhere in the West Indies in late Tertiary time The release of stress from this area by movements along the Bartlett fault must be very effective Indirectly it offers proof of the Miocene age of the Bartlett Trough, for if the fault were there during the great Eocene deformation, the Cuban area would not have been so intensely deformed

CONCLUSION

At least one positive conclusion can be drawn from the geophysical and geological study of the West Indies that is, a settlement of the long standing controversy as to whether the Lesser Antilles represent a structural connection between the east-west ranges of the Greater Antilles and the east-west ranges of Venezuela, which are a continuation of the Andean chain, or whether the Antillean ranges and Venezuelan ranges both continue eastward in structures beneath the ocean, perhaps to join the Alpine chains of Europe and northern Africa as some European geologists suggest. The Lesser Antilles are on a geanticline and do represent the structural connection between the Venezuela chain and the Greater Antilles, as Suess originally postulated, and the contrary interpretation may now be discarded

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Notes on Plates (in pocket)

PLATE I TECTONIC MAP

Most of data on tectonic trends on land areas taken from the literature Submerged structures suggested by topography, gravity anomalies, or both Topography from Hydrographic Office charts, the Barracuda Expedition and recent soundings taken by the U S Navy With certain exceptions, sufficient soundings are available to make all major features of the topography show reasonably accurate, though no doubt more soundings would add much to the detail The exceptions to the above statement are the following (1) North of the Gulf of Maracaibo and hence northwestward to the south end of Beata Ridge, (2) A large portion of the area included on this chart of the Atlantic Ocean outside the Lesser Antilles

PLATE II PROVISIONAL ISOSTATIC GRAVITY ANOMALY CHART

The gravity anomalies taken by the four expeditions to the West Indies, as well as a large number of land stations taken by the U S Coast and Geodetic Survey parties, furnish the basis for the contours The stations at sea are widely spaced If a closer net of stations were taken, no doubt a much greater complexity in detail would be found, just as has been found where the stations are closely spaced in Cuba Nevertheless, it is unlikely that the main features of the gravity field as shown would be materially changed The anomaly field from eastern Venezuela to north of Bonaire is doubtful The probable former extension of the negative anomaly strip into Colombia is indicated only by the geology A narrow east-west positive area crossing central Puerto Rico has been omitted

THE ROLE OF EARTHQUAKES AND THE SEISMIC METHOD IN SUBMARINE GEOLOGY

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The thought of an effective attack on the problems of submarine geology is rather appalling in view of the vast extent of the oceans. To bring the problem within reasonable bounds there must be limited objectives The problem is so new that even these cannot be attained without the continuing development of fundamental methods There is need for careful selection of areas which would be suitable both for the development of methods and also for furnishing valuable results when attacked by these methods My purpose is to show that seismic considerations will prove a useful guide in the selection of these areas

Earthquakes are associated with mountain structures whether of the continents or of the island arcs and with their associated deep ocean troughs They are known to occur along the great rises or ridges in the Pacific, Indian and Atlantic Oceans and the inference is reasonable that these are mountain structures, especially as earthquake epicenters are relatively rare in the adjoining ocean basins. If these rises are mountain structures, their surface expression is probably very different from that of continental mountains Even if they may have once been above the sea, they have undoubtedly been submerged for vast periods when no transfer of material by erosion and deposition could take place

The first feature to be discussed is the Mid-Atlantic Ridge which writers have associated with the lost continent of Atlantis and which has also been considered a remnant left behind in the parting of the continents according to the

Wegener hypothesis of continental drift The idea comes from the peculiar and indeed unique configuration of the Ridge which extends the entire length of the North and South Atlantic Oceans and which, throughout its length is approximately half way between the continents and roughly parallel to their shores

The information regarding the Mid-Atlantic Ridge is quite inadequate and it is even rather difficult to outline its boundaries The 12,000 foot or 2000 fathom curve has been selected (Fig 1) and on this basis the Ridge has widths varying from less than 100 miles to nearly 700 The part of the Ridge which has deep water on either side from about 53° N Latitude to 36° S Latitude has an area of 2,750,000 square miles or about 11/12 that of the United States The part of the Ridge which has less depth than 1500 fathoms is outlined, but the information is too inadequate to make it possible to show other curves of less depth The Ridge in general rises from 3000 to 6000 feet above the ocean bottom on either side, though some of the island peaks rise as much as 18,000 to 20,000 feet above it North of 53° N latitude the 2000 fathom curve is discontinued because of the decreasing general depth of the ocean and the approximate 1500 and 1000 fathom curves are shown

It is of interest that the first recognition of the existence of a ridge came in 1854 in the course of the surveys for the first transatlantic cables The discovery of Faraday Hills with a depth of less than 700 fathoms gave rise to a hope which was not realized that a great plateau of moderate depth would be found The actual depth over most of the Ridge is considerable

The curves shown between 60° N and 47° S are taken from three bathometric charts of the International Hydrographic Bureau at Monaco all of which have been revised to within the past two years The knowledge of the southern portion of the Ridge is to be credited largely to the work of the German surveying ship *Meteor* since the World War However even the most casual inspection of the charts shows

the great need for additional soundings and makes it clear that nowhere have the surveys been intensive.

Figure 1 shows how closely the earthquakes are confined to the Ridge, how much of the Ridge has been seismically active in recent years, and how comparatively few are the earthquake epicenters in the basins on either side except between the Azores and the Iberian Peninsula. It is of interest, though beyond the scope of this paper, that the earthquake activity of the Ridge extends into the Arctic Regions, passing between the North Pole and Siberia and entering the continent to join the major earthquake belt in the vicinity of Kamchatka (Fig 2)

The activity of the Mid-Atlantic belt was first worked out by Tams (1) for the period 1908–1926. There were many earlier reports from vessels experiencing earthquakes, especially in the equatorial portion, but since the uncertainty of the determinations may be on the order of 100 miles, these have not been included Even in the case of instrumental determinations the recording stations are so distant that there is considerable uncertainty The positions given by Tams for the period 1913–1926 in many cases differ materially from those given in the International Seismological Summary.

The earthquake areas outlined in figure 1 are made sufficiently large to take account of the uncertainty of position of the epicenters In the absence of seismograph stations along the Ridge, only those earthquakes sufficiently strong to be recorded at distant stations are located and all others escape record. This is especially true of the southern portion The long gaps between regions of seismic activity along the Ridge shown in figure 1 would probably be much shorter if all the earthquakes could be recorded, or if, even under present conditions, the record had extended over three hundred years, the approximate length of the oldest earthquake history of the United States Imamura (2) considers even this period very short for the appraisal of the seismicity of a region

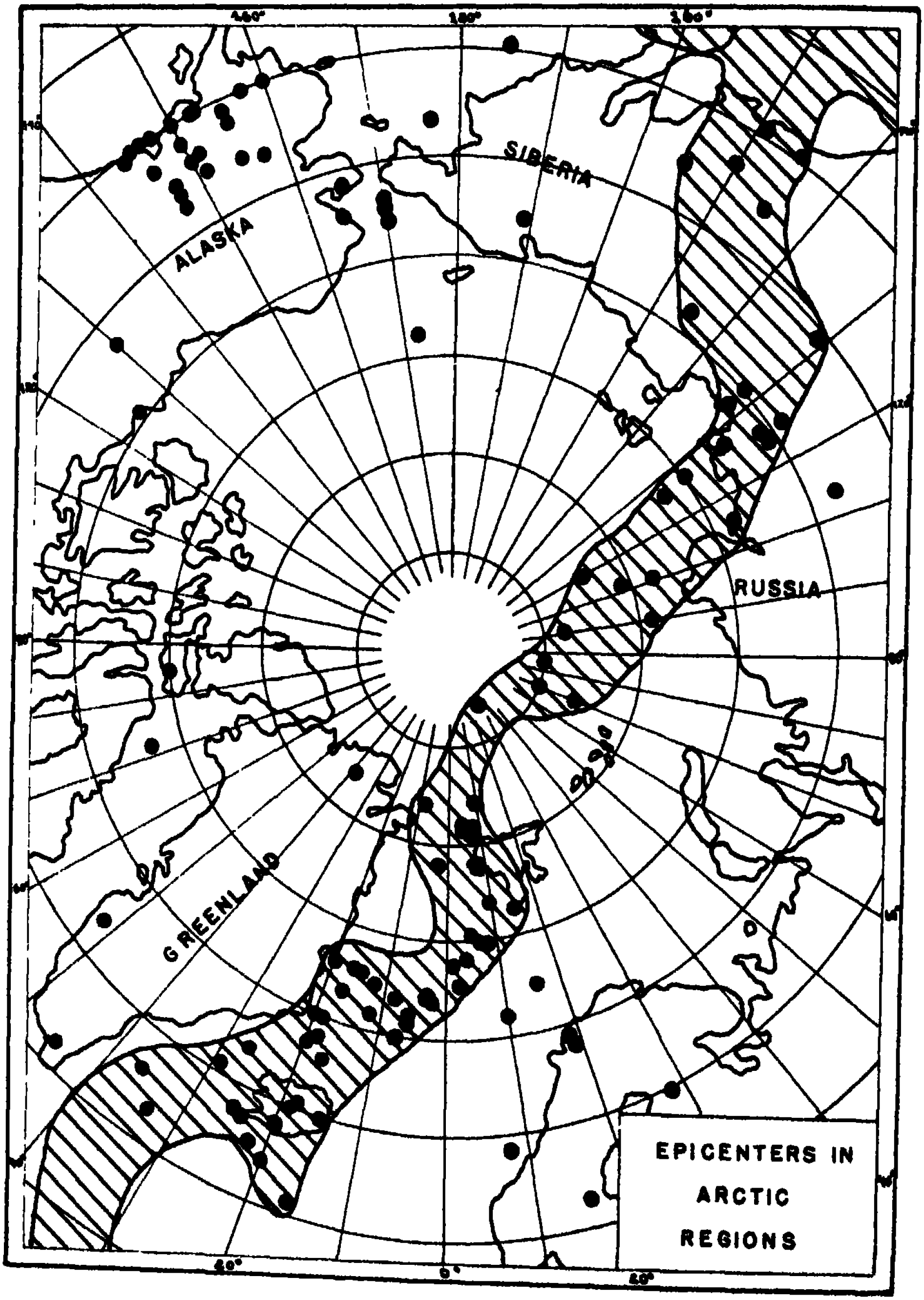
160°
180°
160°
SIBERIA
ALASKA
RUSSIA
GREENLAND
EPICENTERS IN ARCTIC REGIONS
20°
0°
20°

Fig 2

However there is sufficient evidence to show that while there are destructive earthquakes in the Azores and others of equal intensity at a number of places along the Ridge, the equatorial portion has the largest number of severe earthquakes

The Ridge is without connection with the continents except for Walfish Ridge in the south Likewise there is no connection with other earthquake belts except possibly to the east of the Azores The western boundary of the Mediterranean portion of the major belt has not been defined and the epicenters shown on figure 1 may mean an actual connection between the two belts However the charts indicate neither rises nor deeps though the bottom appears to be quite irregular The distance between the Mid-Atlantic belt and the Caribbean portion of the major Circum-Pacific belt is so great as to preclude evidence of connection

The delineation of bottom contours and the measurement of gravity at sea have been discussed Further information regarding geologic conditions, including layers of discontinuity and to some extent character of the material, can be obtained by the application of seismic methods, using either natural or artificial earthquakes (explosions)

For a number of years the explosion method has been successfully used in shallow water, especially bayous, along the shores of the Gulf of Mexico, to ascertain the underlying geologic structure In 1935 Dr Ewing with others (3, 4) proved that it was possible to do explosion work out to the Atlantic Coastal Slope, which lies about 80 miles off-shore in the region of Chesapeake Bay This work has made it possible to trace the crystallized basement (peneplain) rock beneath the Cretaceous and consequently to follow to seaward a fundamental continental structure whose type and date are known, (Fig 3) A tribute is due to the Geological Society of America which supported the work and especially to the Woods Hole Oceanographic Institute which has made the work possible, as well as to many other cooperating institutions Dr Ewing has authorized me to state that he has recently proved that apparatus developed by him can be used to a depth of 2600 fathoms, though there are still many problems to be solved, and he also considers it possible to explore the bottom materials to a depth of 10,000 feet. (He should be describing this work, except for the requirement that each participator in the symposium covers only one subject)

The application of the explosion method is greatly needed in the study of the Mid-Atlantic Ridge as well as of the ocean basins

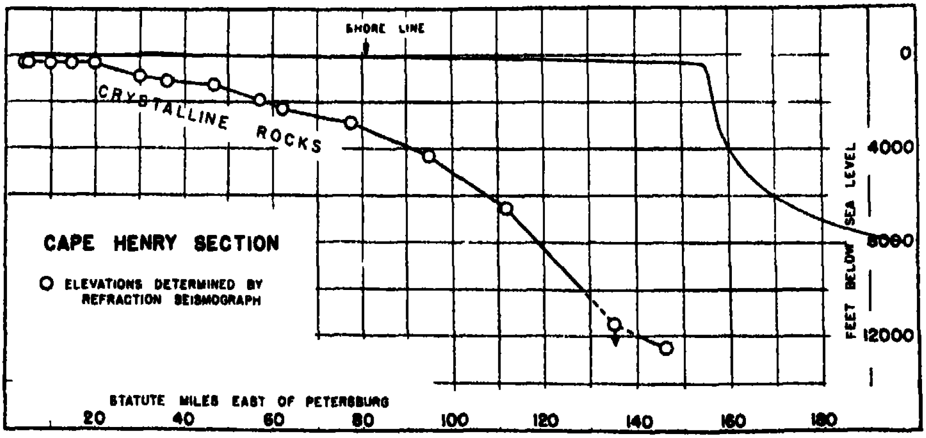

FIG 3 Section showing the surface of crystalline rocks based on refraction seismograph methods by Ewing, Crary, and Rutherford in 1935 Modified from figure 32, p 790, Vol 48, *Bull Geological Soc of America*

Explosions have the great advantage that time and place of occurrence are accurately known However the waves sent out will give only very superficial information unless quantities of explosive, prohibitive in cost and dangerous to handle aboard ship, are used For greater depths it is necessary to study earthquake waves since they penetrate to any desired depth. However for the study of the crust, earthquakes at a distance of only a few hundred miles are needed and special instruments are needed to record them The great difficulty in the case of earthquakes is that the same waves which tell about the condition of the medium through which they pass must also be used to locate the earthquakes including depth beneath the surface and to give the time of occurrence, and the two demands are not independent This fact tends to limit the amount of information that can be obtained and its accuracy

Ordinarily oceanic islands (those which are not merely the surface expression of a submerged continental area) since they are predominantly volcanic or coral, do not well serve the purpose of affording exposures of geologic formations which are one of the chief resources of the geologist on larger land areas There are occasional exceptions and one of special interest has been pointed out by H S Washington (4)—St Paul Rocks in the equatorial part of the Mid-Atlantic Ridge, which is composed of heavily metamorphosed peridotite or dunite, a plutonic rock usually found beneath the granite From this Washington and others have deduced conclusions about the Ridge which should be investigated The essential point regarding suboceanic geology is that the chief dependence must be placed on geophysical methods of attack.

The information regarding suboceanic structure from the study of waves from natural earthquakes is indicated by Gutenberg (5) He finds a layer of varying depth beneath the continents but on the order of 50–60 kilometers, a layer 20 kilometers thick beneath the Atlantic Indian, and southwest part of the Pacific Ocean, and a complete or nearly complete absence of similar layers in the rest of the Pacific and part of the Arctic Ocean The picture is not one of essential difference in surface conditions but rather that the condition beneath the main Pacific is found all over the earth, and that over the Atlantic at a certain depth beneath the continents (Fig 4)

The thickness of the continental layer varies from place to place and the same is probably true for the Atlantic layer It is important that use be made of every earthquake along the Ridge to test this whenever possible.

So far as is known no deep focus earthquake (100 to 700 kilometers in depth) occur on the Mid-Atlantic Ridge Since these are found chiefly along the rim of the Pacific Ocean in its northwest and southeast portion, the inference might be drawn that no unusual forces are at work in the Mid-Atlantic region

From the seismic viewpoint four specific types of area can now be outlined where investigations are feasible by a properly financed expedition which are certain to produce results of major importance

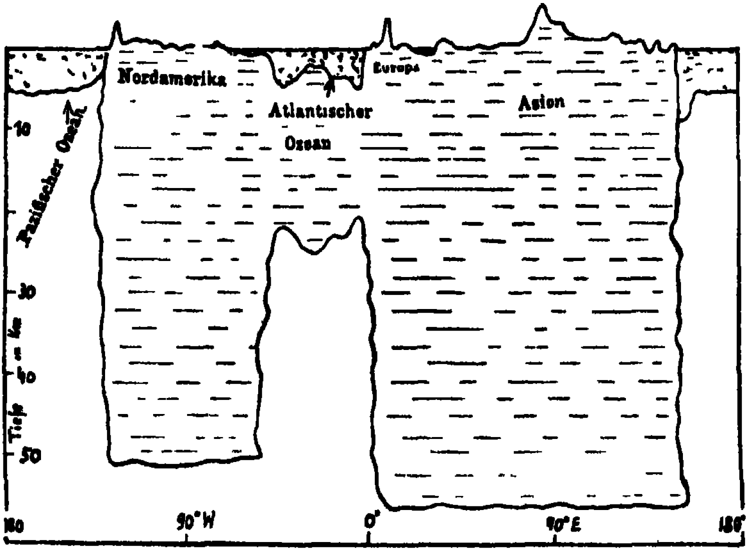

Fig 4 After Gutenberg

1 A ridge or rise area, preferably of the Mid-Atlantic Ridge

2 An ocean trough or fore-deep

3 An area of transition from continent to Atlantic Ocean with particular reference to depth of layers.

4 A similar area for the Pacific Ocean

The complete examination of these areas includes delimitation of bottom contours, with accurate determination of position, determination of character of materials and layers of discontinuity by the use of the seismic method either with earthquakes or explosions, gravity determination, and bottom sampling with geologic study of cores It may not be possible to carry on all of these and all cannot be done by the same expedition but the need for carrying on as many as possible and of coordinating what is done should be recognized

1 Three areas of the Mid-Atlantic Ridge might be considered in the order of their desirability from the seismic viewpoint The first is a portion of the equatorial section of the Ridge, preferably in the vicinity of St Paul Rocks This is a region of severe earthquakes and of great ranges in depth from ocean troughs to slight projection above the surface The chief objection to this choice is the lack of a convenient base of operations for vessels doing sounding, gravity determination and artificial seismic work The next choice is the vicinity of the Azores either to the east or west In this region there are good bases for operations and it is possible to locate accurately all earthquakes Also the depths are suitable for explosion work Study of the area to the east might bring out important relations between the Mid-Atlantic and Mediterranean earthquake belts The third choice is an area in the vicinity of Faraday Hills but this has as its only advantage nearness to Europe

The location of earthquakes along the Ridge is important and does not have to await a special expedition. The requirements, suitable sites and means of continuous operation are hard to meet on oceanic islands The situation in the northern part of the Ridge is going to be greatly improved by the project announced by Dr Anghostino at the Edinburgh meeting in 1936 of the International Seismological Association This is the installation of three sets of Bosch-Omori seismographs at three sites in the Azores, respectively in extreme west, middle and extreme east which will serve well for the location of all the stronger earthquakes Previous efforts to locate the earthquakes from stations on the Ridge itself were not very successful because the instruments installed at Punta Delgada in the Azores, Ascension Island and St. Helena were of the Milne type, now considered obsolete. All published reports of earthquake epicenters have made no use of these stations. A recent station of great value in the northern part of the Ridge is that at Godhavn in Greenland.

The difficulties in the way of improving the situation along the Ridge in general are so great that the only recommendation ventured is for a seismograph at Bermuda which, though at a considerable distance from the Ridge, is well located geographically with regard to it, and which with a suitable instrument would add greatly to the accuracy of location. It fits in well with existing stations in Puerto Rico and Martinique Some attempts are being made to develop a portable seismograph and future expeditions might instal these in their region of operations, during their stay.

There is still much to be learned about the exact relation of deep ocean troughs and the associated mountain structure whether continental or island arcs. Among other things it is important to have more exact contours of the boundaries of the troughs and this would make it possible to associate the earthquake epicenters with the movements which produce them It would be very desirable to trace by means of explosions the basement rock from the shores out to the edge of the deep With complete information many interesting relations develop as has been shown for the troughs in the East Indies and east of Japan. For some of the deeps there is apparently a rather uniform slope between the deep and the shores which does not seem to indicate typical mountain structure.

There are several deeps which might be studied. The most convenient to the United States are the Aleutian and the Nares, the latter following the Antilles on the Atlantic side from Santo Domingo almost to Trinidad. The Aleutian Deep, though better known than formerly would need much additional survey, the two seismic stations of the region at Fairbanks and at Sitka while well placed are rather far away and the region is subject to fogs and dangerous currents.

Accordingly the Nares Deep could well be chosen. While its present earthquake activity is small it might be found much greater with instruments for recording near earthquakes. Additional stations could be readily established Numerous soundings and gravity observations have already been obtained The Bartlett Deep might also be selected

Hess has called attention to the need for knowing the thickness of the layers beneath a Deep. Earthquakes rarely occur in such positions as to give the desired information It has been suggested that either by the use of two vessels or by the further development of the sono-radio buoy of the Coast and Geodetic Survey with a single vessel the problem might be worked out. A portion of the Nares Deep near its end near Trinidad might be used and waves might be sent through the earth with a moderate amount of explosive from one side to the other.

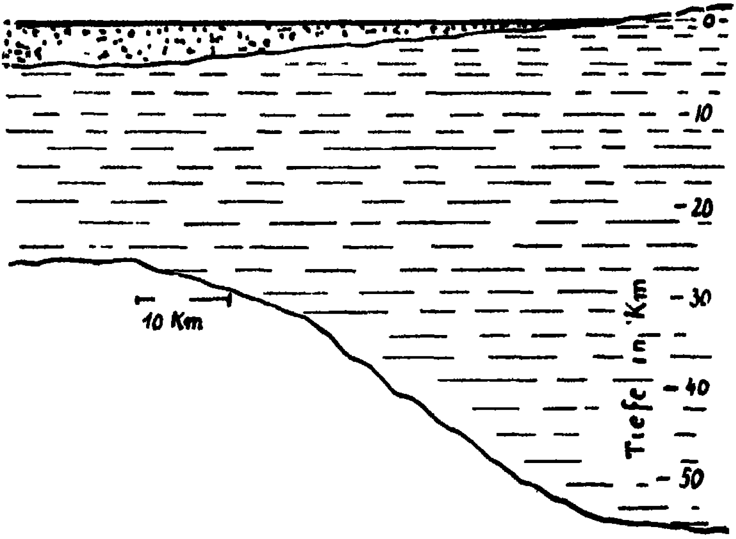

Fig 5 Transition Europe to Atlantic Ocean After Gutenberg

3. The method of transition of the various layers of discontinuity both shallow and deep from the continent to the

Atlantic should be further studied through earthquake and explosion. Gutenberg has inferred the manner of change from 50 kilometers to 20 as gradual west of Portugal, but other determinations should be made. This method of gradual transition is found also in the case of the basement rock by Ewing off the east coast of the United States (Figs 3, 5).

4. In the Pacific Ocean there is evidence that the transition from a layer of perhaps 50 kilometers to zero is abrupt. This would indicate some kind of vertical discontinuity of considerable depth and this is exactly what Gutenberg has found. The transition of the basement rock from land to sea as determined by explosions is also of great interest

In either case the line of attack is through a judicious combination of earthquake and explosion methods so that both the basement rock and the deeper layers are studied. Gutenberg has paved the way for the latter and Ewing for the former. Accordingly it would be well to make the studies for the Atlantic Ocean off the east coast of the United States and for the Pacific off the southern California coast where the available earthquake information is now very complete.

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TERRESTRIAL MAGNETISM AND OCEANIC STRUCTURE

J A FLEMING

Director, Department of Terrestrial Magnetism
Carnegie Institution of Washington

THAT irregularities of the distribution of the Earth's magnetic field over continental areas may bear definite relation to geologic features of the Earth's crust has been recognized for a long time It is only in comparatively recent years that such magnetic data have been intensively considered as an aid in the determination of the character of geologic substructure From accumulated observations it is possible to account for a considerable part of the Earth's field on the basis of a uniformly magnetized sphere The difference between such a uniform or normal magnetization and that actually existing serves to bring out the general irregularities as a residual field (Fig 1). Figures 2 and 3 present this feature in different ways The Earth's outer crust or shell, perhaps 25 or more miles thick, is not homogeneous and therefore is not uniform in its magnetic behavior. Thus there are many regions of local magnetic disturbance, such as are caused by magnetic ore-deposits, some so great as to give rise to local poles and other irregularities of intensity twofold or even threefold the normal value in such regions The anomalies at Kursk, Russia (Fig 4), at Berggiesshübel, Germany, and in New South Wales are a few striking examples of such magnetic irregularities or anomalies The great anomaly in South Africa (Fig 5) apparently retained for over 100 million years by the huge Pilansberg system of Paleozoic volcanic dykes has been recently examined by H Gelletich Fourteen vertical dykes, of horizontal widths between 65 and 350 feet and horizontal extent up to 100 miles, are found to be strongly magnetized in a direction opposite to the present-

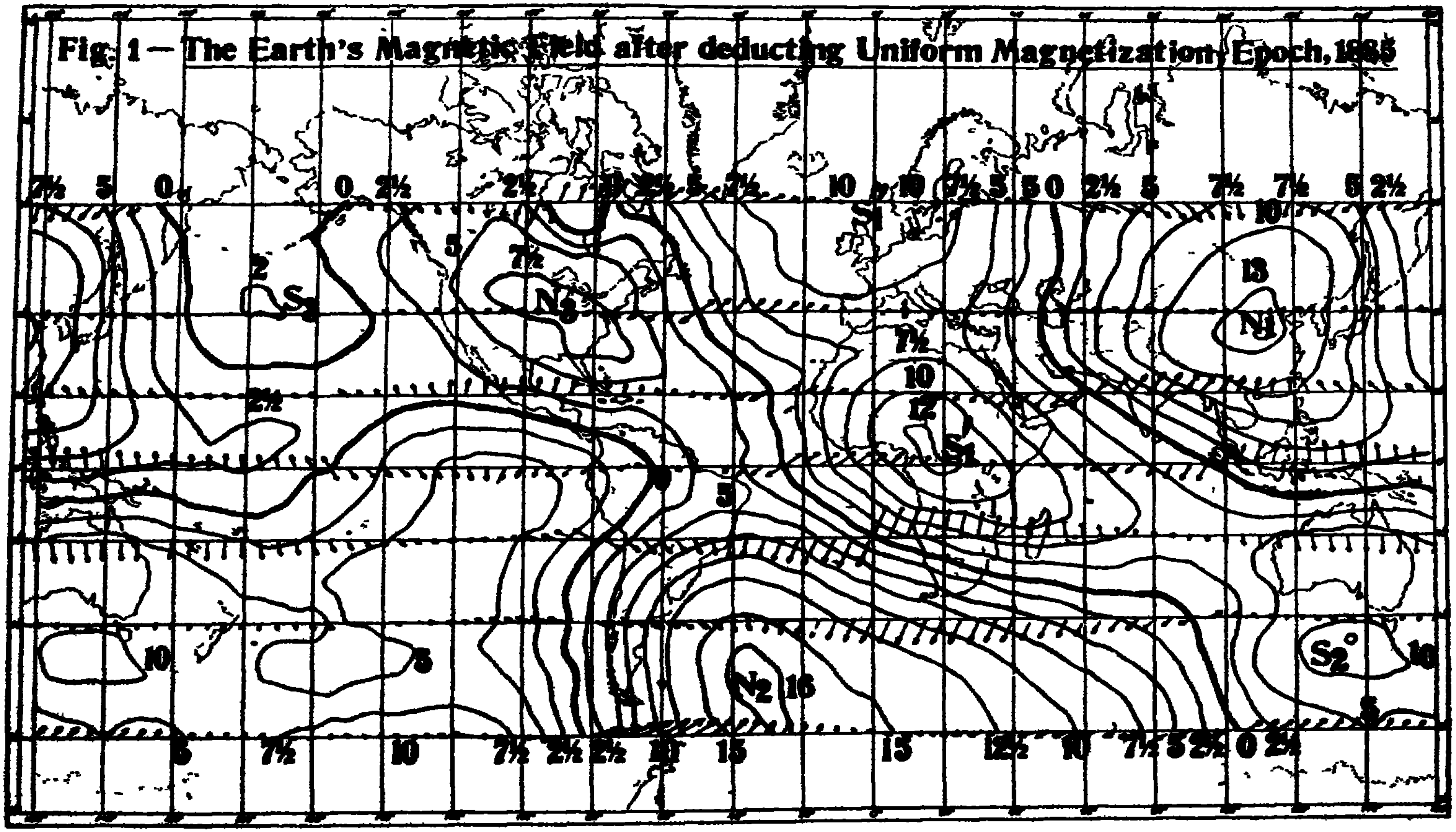
Fig. 1 — The Earth's Magnetic Field after deducting Uniform Magnetization, Epoch, 1885
N1
N2
N3
S1
S2
S3
13
12
10
16
15
12½
7½
5
2½
0

FIG. 1 The Earth's magnetic field after deducting uniform magnetization, epoch 1885 (after Bauer) [The curved lines are the lines of equi-residual vertical force. The arrows give the direction and relative intensity of the horizontal component of the residual magnetic force Over the regions about the poles, N_1, N_2, and N_3, the north end of the magnet is attracted, while over the regions of the poles, S_1', S_1'', S_2, and S_3, the south end is attracted The vertical intensities (large figures) are given in units of the second decimal, CGS[1]

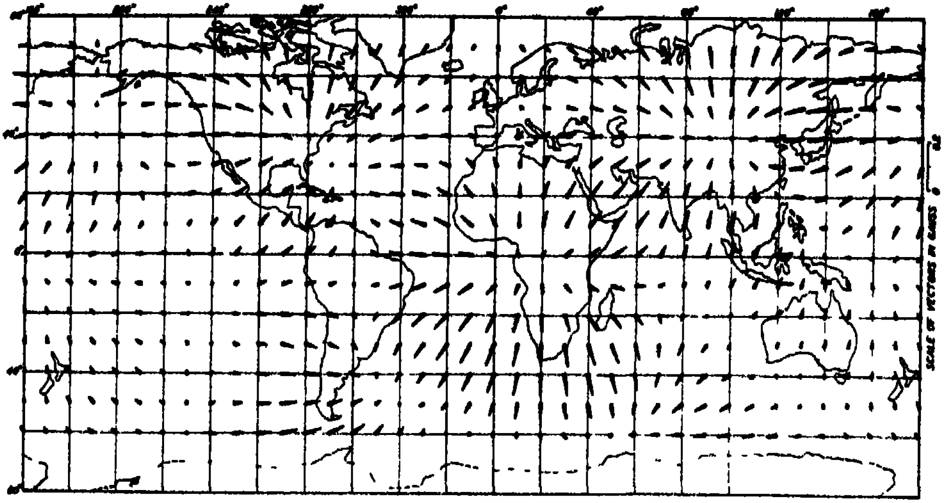

Fig 2 Differences, observed minus eccentric-dipole field, or regional anomalies for horizontal vectors

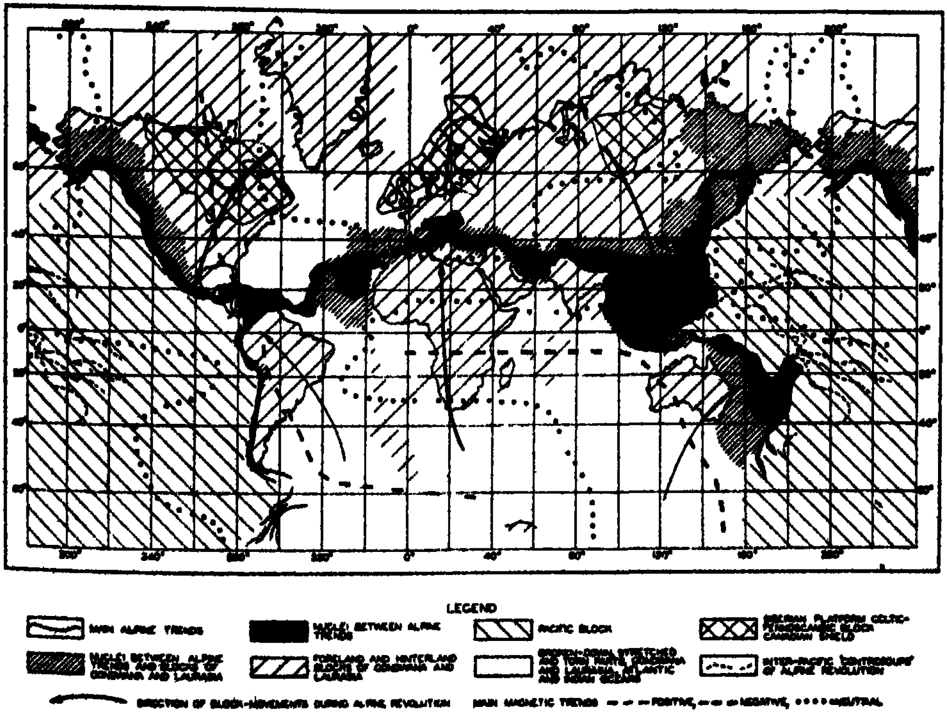
LEGEND
MAIN ALPINE TRENDS
NUCLEI BETWEEN ALPINE TRENDS
PACIFIC BLOCK
CANADIAN SHIELD
NUCLEI BETWEEN ALPINE TRENDS AND BLOCKS OF GONDWANA AND LAURASIA
FORELAND AND HINTERLAND BLOCKS OF GONDWANA AND LAURASIA
BROKEN-DOWN STRETCHED AND TORN PARTS, GONDWANA AND LAURASIA, ATLANTIC AND INDIAN OCEANS
INTER-PACIFIC OF ALPINE REVOLUTION
DIRECTION OF BLOCK-MOVEMENTS DURING ALPINE REVOLUTION
MAIN MAGNETIC TRENDS POSITIVE, NEGATIVE, NEUTRAL

Fig 3 The main Alpine trends and magnetic trends of the Earth (after R Staub and Jenny).

day magnetic field of the Earth In this general region of South Africa the magnetic horizontal component of the Earth's field has decreased 16 per cent of its present value in a 30-year period!

The anomalous magnetic features thus observed over continental areas must have their counterparts in the great oceanic basins We therefore may look confidently to such features as an aid in the study of oceanic structure Indeed, observations made on isolated islands and island groups almost invariably indicate abnormal magnetic conditions, and the magnetic survey of the oceans by the Carnegie Institution of Washington since 1905 (Fig 6) has revealed such conditions at sea

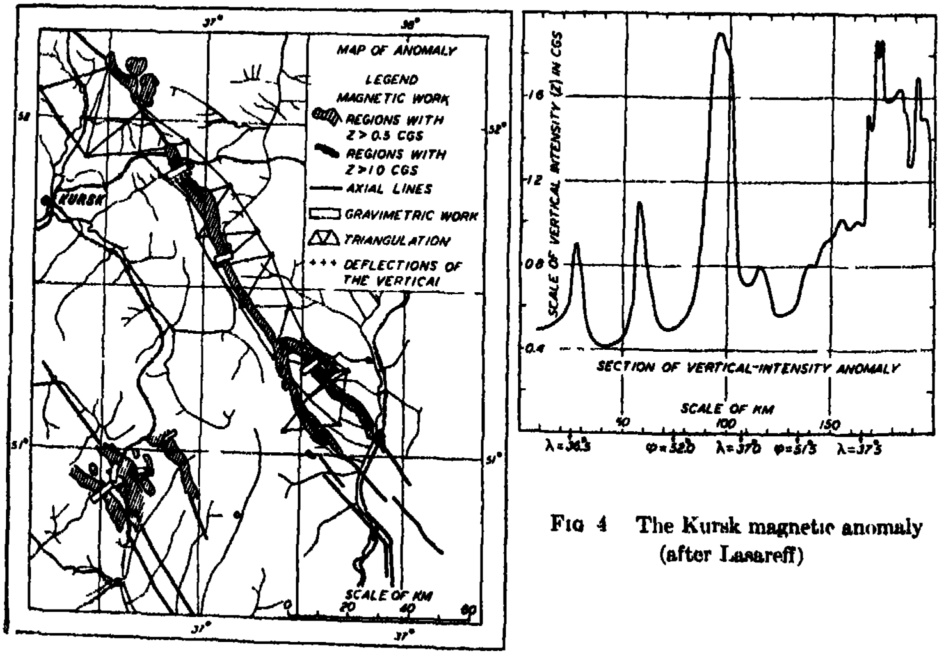

Fig 4 The Kursk magnetic anomaly (after Lasareff)

However, the application of magnetic-survey results to the investigation of crustal features of the ocean bottom depends upon the existence of a difference in substructural physical properties as well as upon the magnitude of this difference. Here enters the magnetic susceptibility of rocks, some of which are strongly magnetic, as iron-ores and igneous and metamorphic rocks, and some weakly magnetic, as most sedimentary rocks. Here, then, one must think of the observed magnetic anomalies as a kind of general reconnaissance method to indicate areas for other more intensive geophysical studies. However, the magnetic method of

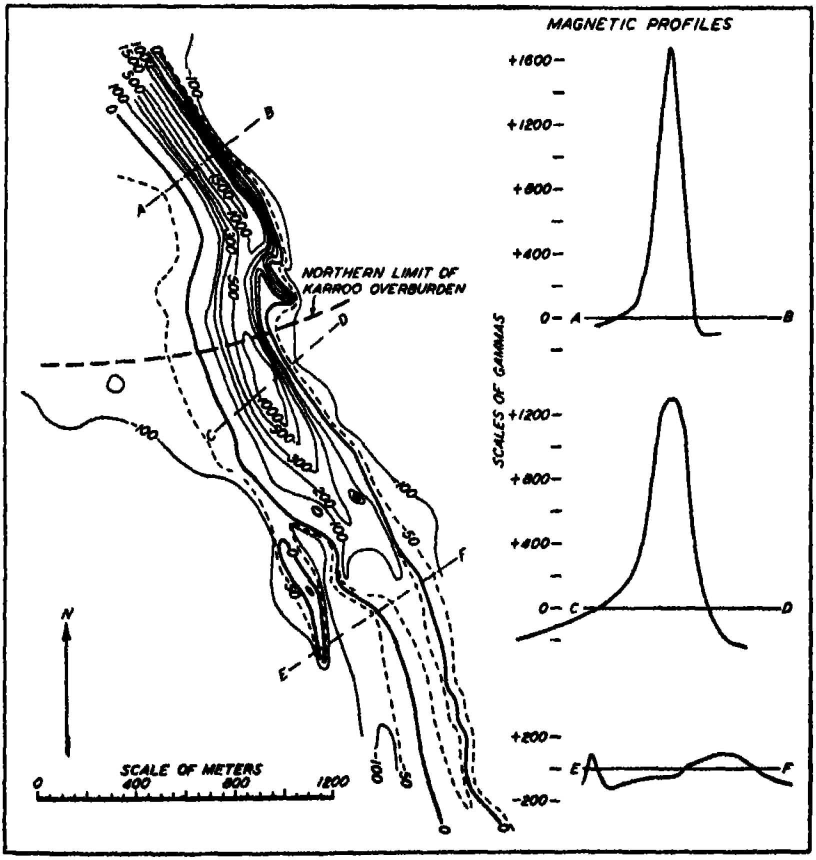

FIG 5 Magnetic anomaly of Pilansberg Dyke System, southern Transvaal, showing anomaly of vertical intensity expressed in gammas (after Gelletich)

approach lacks depth-control, and therefore the size of geologic features must increase in proportion to depth if we are to detect such features Thus, unless the magnetic anomaly observed at sea is over shallow water or if over deep water is of enormous proportions, there may not be great hope of immediately deriving very exact information regarding particular areas of bottom substructure from distribution data as shown only by isomagnetic maps

The Earth's magnetic field is subject to changes with time, that is, secular variation – a phenomenon, adequate data for and investigation of which afford a field of large potential value in the study of the Earth's crust Herein is the great need of continuance of the accurate magnetic survey of the oceans that we may determine the character of such changes with epoch and their accelerations at various places.

Ever since the discovery of the change in the Earth's magnetic field through the centuries, investigators have noted the apparent asymmetry and regularity of secular variation when attention is confined to a single station or to a small part of the Earth's surface such as western Europe—only one-hundredth of the Earth's surface. Considering, however, the actual observational data when the whole Earth is taken into account, secular variation is not so simple a phenomenon that it may be explained by periodic movements of the Earth's magnetic poles and the like, but is a regional phenomenon connected with a large geological structure—oceans and continents—of the deeper layers of the Earth's crust

Secular-variation data are determined from isomagnetic charts for various epochs (Fig. 7). Changes in compass-direction due to secular variation are shown in Figure 8. In succeeding epochs, shifts of the isomagnetics occur. Lines or contours joining points of equal change are called isopors. The foci of rapid isoporic changes (Fig 9) raise questions of broad geophysical significance Isopors in vertical intensity are shown by Figure 10 A large part of these changes may have origin in influences impressed by forces

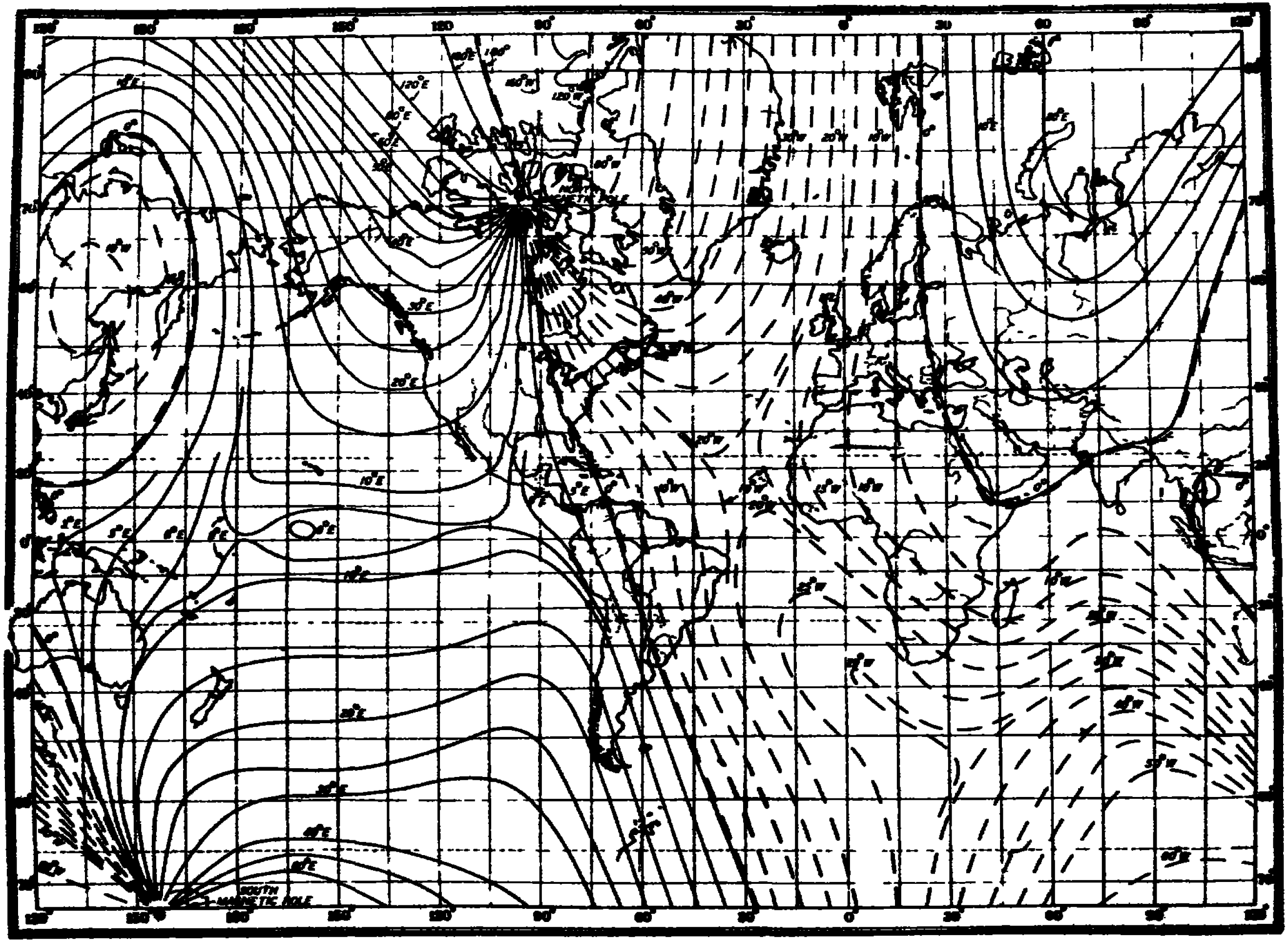

Fig 7 World isomagnetic chart showing lines of equal magnetic declination, epoch 1935

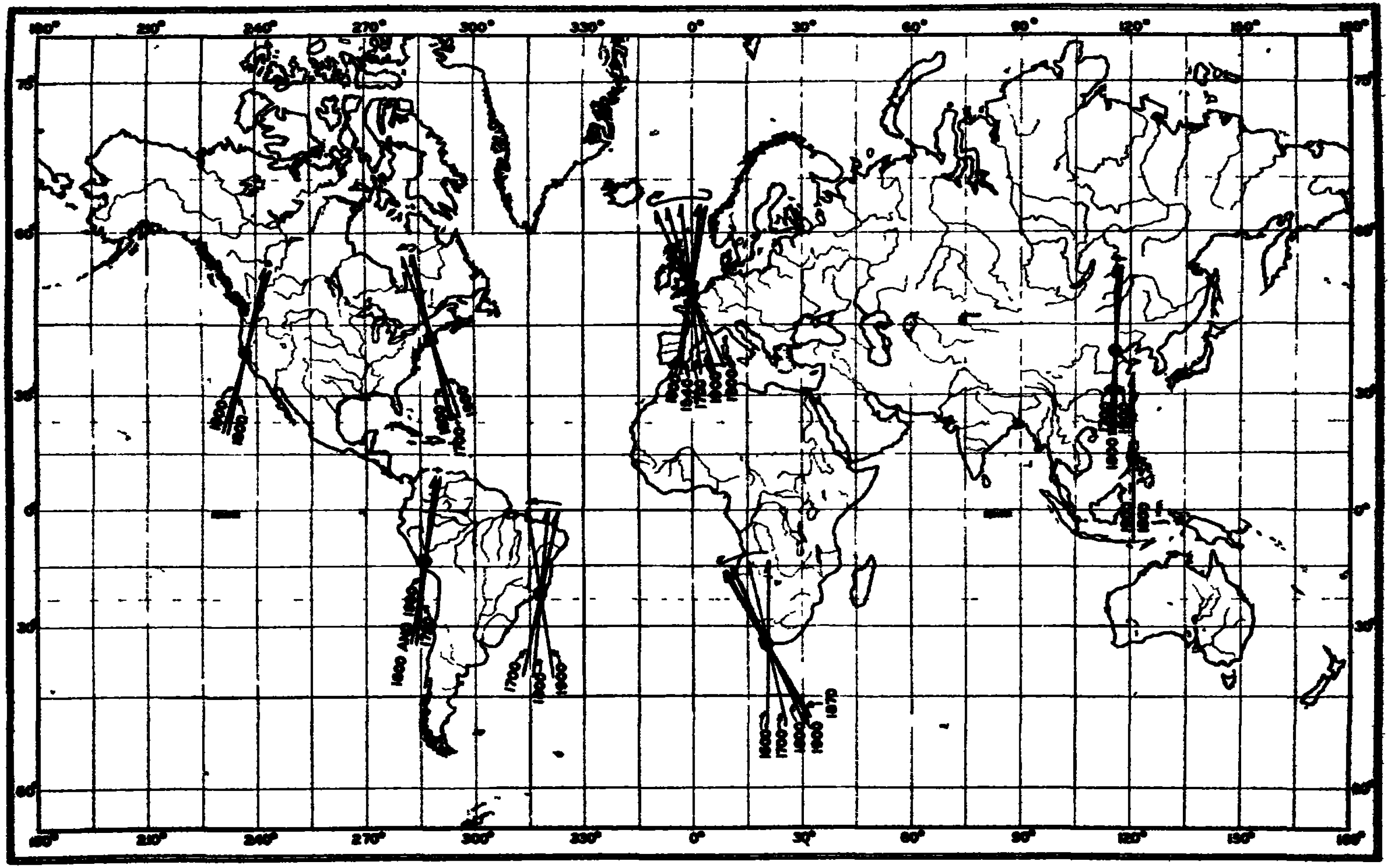

Fig 8 Compass-direction at 1540, 1600, 1700, 1800, 1900, for various stations

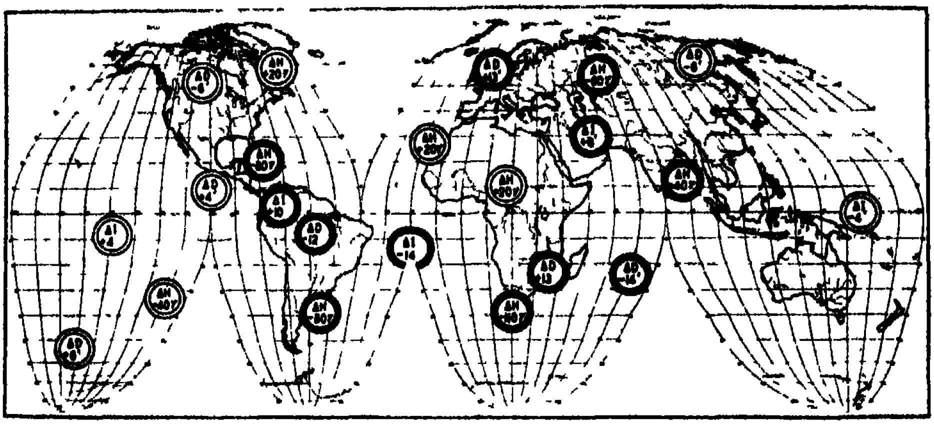

FIG 9 Distribution of foci of rapid annual change of the magnetic declination, inclination, and horizontal intensity, approximate epoch 1920–1925 (after Fisk)

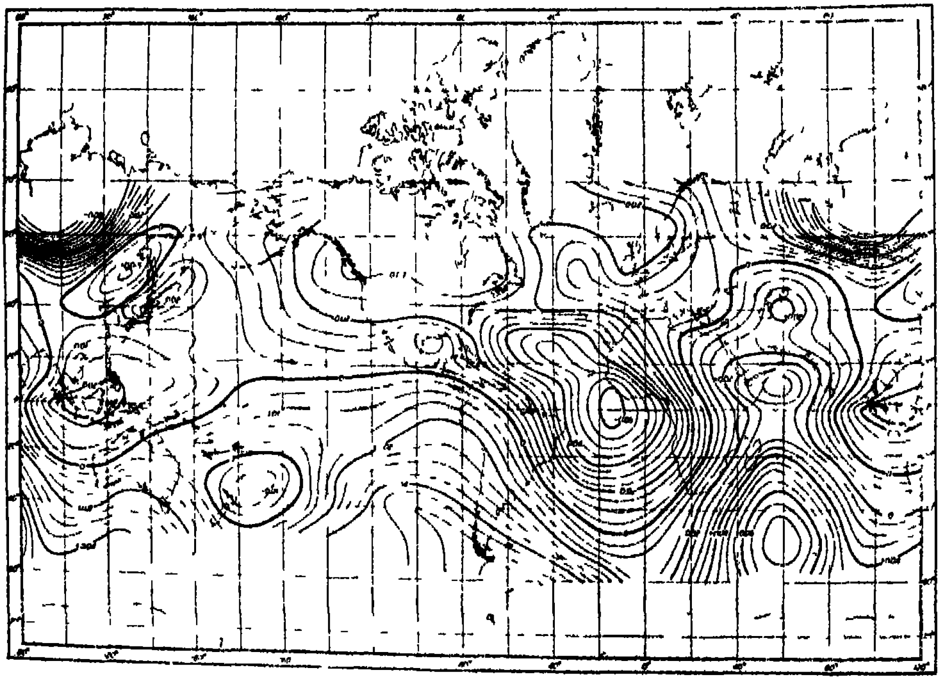

FIG 10 Isopors total secular change in vertical intensity, 1885–1922 [isopor-interval 0 005 CGS unit, increase of downward magnetic force considered positive]

ceaselessly at work deep within the Earth. The rise and fall of the rate of secular change and the slow expansion and then the gradual retraction of the areas within which there have been excessive alterations in the magnetic elements are significant of such changes (Fig 11) The distribution of isoporic foci is noteworthy. They are practically all in the hemisphere containing the great land-masses with the intervening Atlantic Ocean Such foci as are found in the Pacific

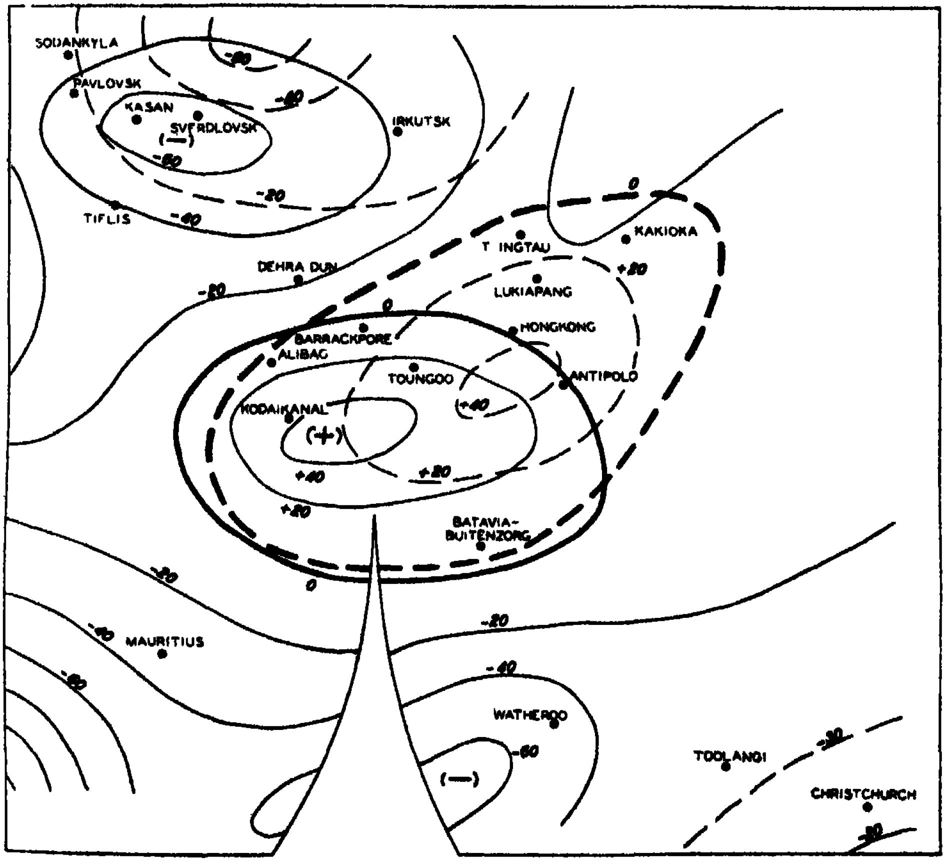

Fig 11 Change in position of horizontal-intensity isopors, 1906–1918 [dashed lines for epoch 1906, solid lines for epoch 1918]

Ocean are of but moderate intensity and not well defined. These relations to the surface structure of the Earth can be scarcely accidental, it is natural to suspect that there is a causal relation between crustal or subcrustal movements and conditions and these magnetic manifestations.

As an example, attention may be called to the apparent diminution of the intensity of the Earth's magnetic field which is marked over oceanic areas, especially in the Southern Hemisphere The interpretation of such data doubtless will be important in geophysical and geological research to advance understanding and interpretation of Earth phenomena

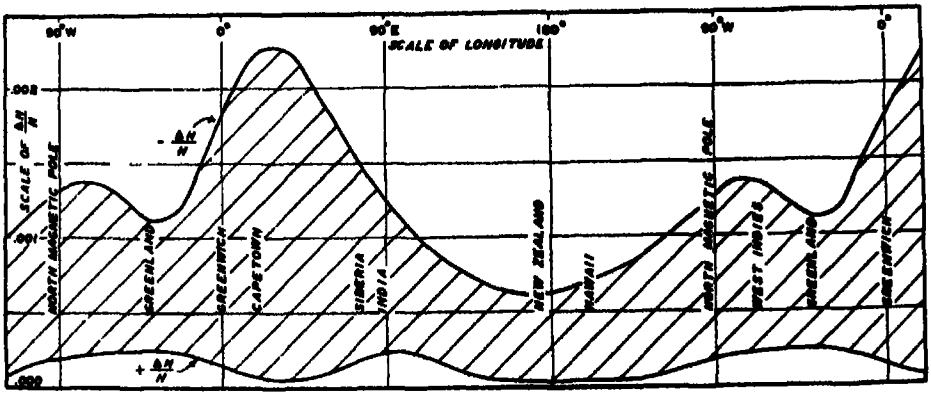

FIG 12 Longitudinal distribution of proportion of annual change [$\Delta H/H$] of horizontal intensity (after Fisk)

For example, from observed earthquake-wave velocities and reflections for different regions and depths, Gutenberg estimates that the crustal layer, which under most of the continental and water-covered continental structures is about 25 miles thick, is either lacking or quite thin under the Pacific Ocean including possibly the arctic region. Under the Atlantic and Indian oceans this layer is of appreciable depth. Thus under the Pacific Ocean the basic surface of the Earth's mantle is practically exposed There then we may expect different geological and geographical properties from those found elsewhere Thus the observed longitudinal distribution of magnetic secular-variation (Fig 12) agrees with that of land-areas (after Fisk, based upon data from 75° north to 65° south *)—as witness the moderate rates of annual change over the Pacific as compared with those over the Atlantic and adjoining continental areas A definite control is necessary for a number of epochs to facilitate the investigation of causes producing and governing these progressive changes which, it appears, would be favored by accurate knowledge of their accelerations and distribution The importance of

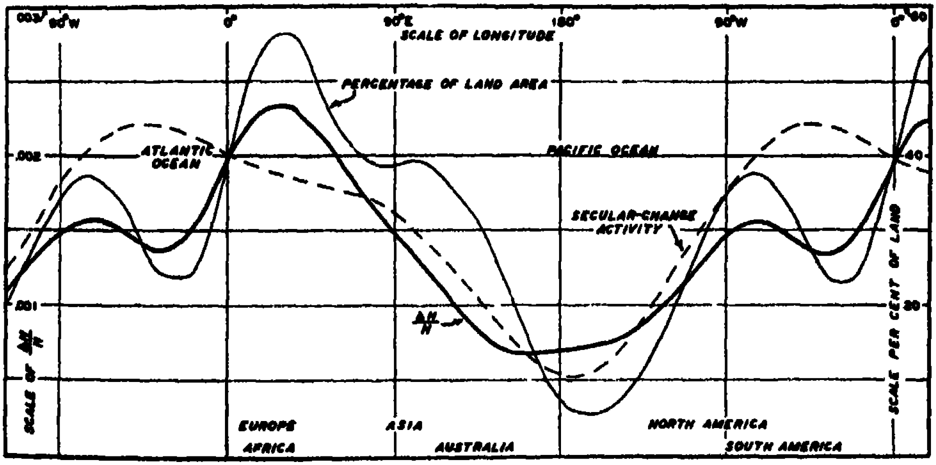

FIG 13 Variation with longitude of $\Delta H/H$ [annual change averaged without regard to sign] of the distribution of the proportion of land and water areas and of secular-change activity approximately determined by the density of the distribution of isoporic lines (after Fisk)

the determination of secular-variation over the oceans may be readily seen by a study of Figure 13

Further data bearing on correlation thus indicated between the surface-distribution of the secular-change activity promise conclusions concerning secular-variation processes localized in the crustal layer and only where this layer is present.

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* In this graph showing distribution of annual change ($\Delta H/H$) of magnetic horizontal intensity the lower curve represents the average positive values of $\Delta H/H$ in each lune between the meridians, while the upper curve represents the numerical magnitude of the average negative values Thus the shaded areas between the curves are measures of the excess of the negative over the positive annual change

Thus continued secular-variation surveys at sea should bring together seismic and magnetic methods of approach to crustal adjustments and possibly gravimetric work

There is an interesting possibility by which secular-variation information may be extended to times more remote than those for which observations exist. When lava cools and freezes following a volcanic outburst, it takes up a permanent magnetization dependent upon the orientation of the Earth's magnetic field at the time This, because of small capacity for magnetization in the Earth's magnetic field after freezing, may remain practically constant. If this assumption be correct, the direction of the originally acquired permanent magnetization can be determined by laboratory tests provided every detail of the orientation of the mass tested is carefully noted and marked when it is removed.

Just as lavas cooling through the Curie-point in the presence of a magnetic field become magnetized in the direction of the field, so sediments containing microscopic magnetic particles also assume the direction of the prevailing magnetic field This is in its truest sense "fossil" magnetization for the magnetic field of the epoch of deposition is embedded in the sediment as surely as the organic remains of that epoch Whether this fossil magnetism remains as a connate property of the rock or whether it is destroyed by subsequent events even as organic fossils are sometimes destroyed, depends upon the postnatal experience of the sediment. In so far as it remains, it may supply a valuable record of the Earth's magnetism and an important clue to the history of the rock

One of the projects outlined in the original program of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington was the measurement of the Earth's magnetism at great depths in the sea This project may now be consummated by magnetic examination of the core-samples taken with Dr Piggot's apparatus described in an earlier paper. In order that the fossil magnetization of the specimens may not be disturbed, a method of measurement has been developed at the Department permitting tests of high sensitivity and accuracy without submitting the specimens to artificial magnetic fields. The cores are cut into one and one-half centimeter cubes, these are rotated in a coil containing many turns of wire (Fig. 14). The voltage generated in the coil is introduced into a tuned amplifier, and the alternating-current output of the amplifier is commuted and measured by a sensitive galvanometer. This equipment permits detection of the magnetic moment of a good steel magnet one millimeter long and one-hundredth of a millimeter in diameter. Through further refinements it is

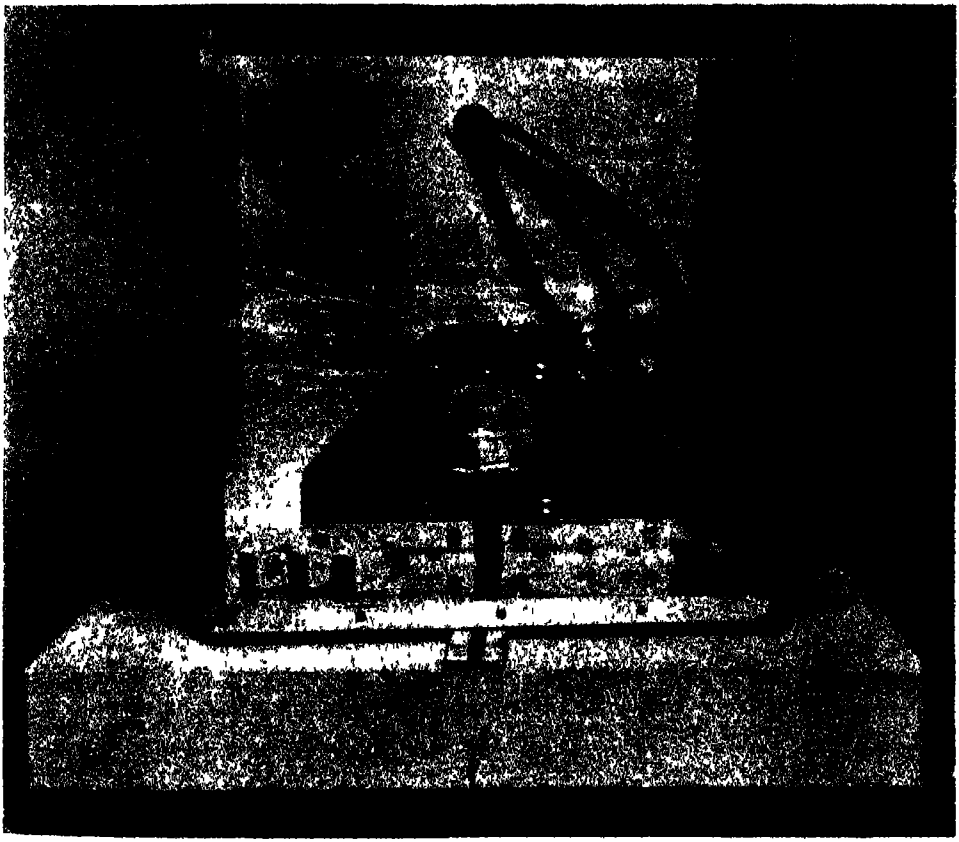

FIG 14 Apparatus used for testing "fossil" magnetization

expected the sensitivity of this method can be increased manyfold.

Tests just conducted on one core show distinct differences in the direction of magnetization at various depths Decision as to whether or not these differences are the result of differences in the Earth's field at the time the sediments were deposited must await further study If such is found to be the case, we have in the core-samples a means to extend the past history of the Earth's magnetism Through interrelating individual cores by similarities in their magnetism, it may be possible ultimately to magnetically date the rocks.

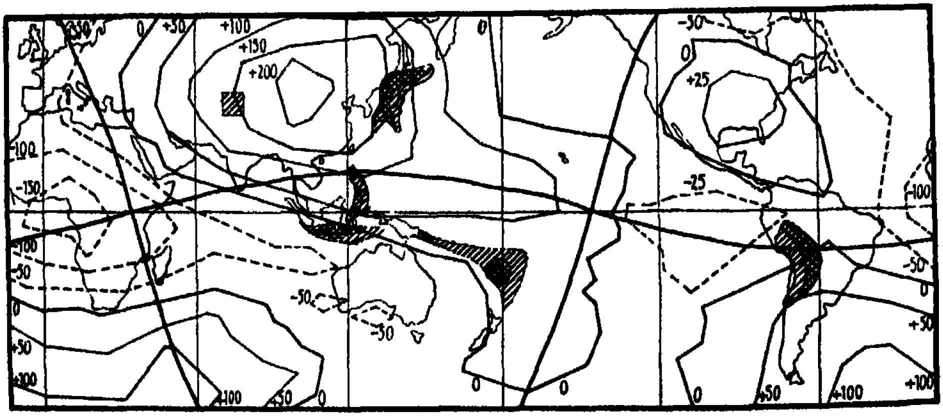

Fig 15 Anomalies of vertical component [0 001 CGS] and principal deep-focus regions (after Visser)

This, too, would determine more accurately than surface observations the extent and character of the regional magnetic anomalies of the ocean bottom

With improved knowledge of magnetic anomalies the question of interrelations with gravimetric anomalies and deep-focus earthquakes may be answered It frequently is noted that gravimetric and magnetic anomalies occur in the same regions. Visser has recently noted an apparent relation that areas of deep-focus eathquakes are confined to the great regions of positive anomalies of magnetic vertical intensity around the Pacific Ocean (Fig. 15) Vening Meinesz has found an excess of gravity in the oceans and a sudden decrease at the continental borders, and has demonstrated these deviations of isostasy cannot be situated in the Earth's thin crust but must extend far into the plastic layers below There must result current-systems in the Earth's interior, downward below the oceans and upward below the continents The chart of isoporic foci and their motions with time certainly lend strength to the idea indicating the interior of the Earth more mobile than the external layers, not only as a whole but regionally Visser queries whether such interior currents may not convey material with special magnetic properties from the depth accounting for positive disturbances at the crust May not then the anomalies of gravity and of terrestrial magnetism and the deep earthquakes have a common origin in current-systems in the inner Earth?

In conclusion, the facts of the geophysical observer of terrestrial magnetism in the field and in the laboratory may contribute much in the formulation of a complete picture of the Earth's crust and particularly of that great portion which is the ocean bottom

ROUND TABLE DISCUSSION

PARTICIPANTS ADDITIONAL TO SYMPOSIUM SPEAKERS

ALFRED C LANE, Chairman Committee on Age of the Earth, National Research Council, in the Chair

WILLIAM BOWIE, Chairman, Projects Committee, American Geodetic and Geophysical Union
ROY E DICKERSON, Chief Geologist, Venezuelan Atlantic Refining Company
E A ECKHARDT, Geophysicist, Research Department, Gulf Oil Companies
C L GARNER, Chief, Division of Geodesy, U S Coast and Geodetic Survey
W H HOBBS, Department of Geology, University of Michigan
W J HUMPHREYS, Director (retired), U S Weather Bureau
CHESTER R LONGWELL, Chairman, Division of Geology and Geography, National Research Council
Chairman, Projects Committee, Geological Society of America
H N RUSSELL, Director, Halstead Observatory, Princeton University
PAUL S SMITH, U S Coast and Geodetic Survey
W T THOM, JR, Chairman, Committee on the Geophysical and Geological Study of the Continents, American Geodetic and Geophysical Union
T W VAUGHAN, Director (retired) Scripps Institution of Oceanography

ALFRED C. LANE, *Chairman* Members of The American Philosophical Society and Guests It has been suggested that we stand in memory of Admiral Patton * (All rise and stand for a moment)

MR FIELD May I say a word in connection with Professor Vaughan's book, "International Aspects of Oceanography," just published by the National Academy of Sciences, Washington, D C, which appears to be a very comprehensive work, and which I believe some of us have not had the opportunity of going over as yet? It will soon be available, and I think that it ought to be called to the attention of this conference

MR. VAUGHAN: I hoped my book would be distributed before this meeting. There are articles in it which deal with various topics presented here—a chapter by Vening Meinesz, a chapter by Gutenberg, by Heck, and so on, and it ties in exactly with the discussion here

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* Director Coast and Geodetic Survey, d Nov 25, 1937

MR HOBBS Mr. Chairman, I have been thinking a good deal of what Mr Hess brought out, and later Mr. Heck, in connection with the island arcs—especially those off the Pacific Coast—and this had to do with the position of the great deeps, with the position of gravity anomalies, and their negative character particularly, but more especially of the great abnormality of gravity along these interesting arcs, and there was also something said about the presence of ultra-basic rocks under these same regions It was said, I think by Mr Hess, that the ultra-basic rocks in connection with these arcs belong to the first stage of the deformation My own study of these arcs is exactly of the opposite character, namely, that the first effusions in connection with the formation of these arcs where the volcanoes appear on the inner or back side of the arc, are universally acidic or of moderate acid character, and that basaltic effusions are always further back toward the interior and belong to a later deformation, and I have produced a map covering a good part of the earth which shows this

I have also taken up in my book, that is not at all well known, and may not have been in the minds of the speakers, the position of the deep in relation to the arcs In the case of arcs of large radius and curvature, the great deeps uniformly appear on the convex side of the arc, whereas as I stated, a good many years ago, in the cases of many of the arcs with small radius of curvature, the deep is on the inside of the radius of the arc, contrary to the general rule which applies to the arc of large radius. I thought the statement of the other speaker was in contravention of that position

MR HESS I tried to say if there were two or three deformations in the region, the *ultra-basic* rocks belonged to the first I had no idea of correlating other intrusions with the tectonic action West Indian deformations took place about the beginning of Upper Eocene and again in Miocene-Pliocene time The ultra-basics go with the first deformation, but not with the second The ultra-basics are serpentinized peridotites

Mr Russell Mr Chairman, I hesitate to talk on some of these things, but the question of where the ocean water went when submarine canyons were formed interests me According to the Hess-McClintock hypothesis the zone at which the ocean level did not change relative to the earth's surface was at approximately thirty-five degrees latitude—I don't know the minutes and seconds, because it depends on how large an area was land and how much was water within the torrid zone—but it has to be extensive land to change things much How did the water get out of the ocean? It has occurred to me that it might be by the locking up of the water in the Arctic regions in the form of ice Grant that precipitation is very low over the Arctic basin, and suppose that great glaciation occurs in several regions—say, to put it crudely, in almost a ring around the Arctic Circle—suppose there were huge masses of ice piling up there, wouldn't it flow northward as well as southward, and would not the glacier gradually fill up the Polar Basin, if there were time enough and ice enough, even if there was no heavy precipitation in the Central Polar Basin? Wouldn't that permit filling up the Arctic Basin chock-a-block to the bottom?

Mr Hobbs Mr Chairman, I do not think it is true that precipitation in the Polar Region is very low I think it is quite the contrary, especially for the Antarctic Region Consider the amount of moisture which goes away in the form of icebergs, and the amount of snow which is driven off in blizzards in the Antarctic Continent goes up into astronomic figures practically I am not classing both Polar regions together One is a very high plateau—a great dome of ice— and enormous masses of moisture go away in the form of snow and icebergs, some of which are ninety miles long Greenland, of course, in the Arctic, is of similar character, but not so extensive

Mr. Dickerson Years ago in the Philippines we investigated the ocean bottom and had the rare opportunity of making an investigation not only of the topography of the entire island deeps, but of the topography of the surface as well.

There is one test of the ice cap theory that has not been applied—the biologic test Incidental to these studies, we had at that time in Manila a botanist and a zoölogist of eminence who had been there the space of twenty to twenty-five years, so from their data we were enabled to divide the Philippines into sub-provinces both faunally and florally

The central islands of Panay, Masbate, and Negros are separated by water only about two hundred feet in depth That constitutes a faunal and floral province. That is just about the requisite depth for land connections during interglacial times. The other provinces of the Philippines were exceedingly distinct from the central provinces of Panay, Masbate and Negros.

Another line of attack can be applied to the hypothesis of these vast withdrawals of sea water. Mediterranean oceans or mediterranean seas, properly speaking, occur not only in the type Mediterranean, but in the Philippines as well. These mediterranean seas would be vastly altered by a lowering of sea level by two thousand feet. Take the Mediterranean for example; if two thousand feet of water are withdrawn, the entrance of sea water into the Mediterranean would be stopped at once because at Gibraltar there is a depth of only three hundred twenty meters. There is an example of what would happen in the Black Sea which is separated from the Mediterranean Sea by a depth in the Dardanelles of fifty to seventy meters—just about Daly's estimate of the withdrawal of sea water in the glacial period.

By means of certain island floral and faunal provinces and by study of mediterranean seas it is possible to get a check upon the possibility of withdrawals of sea water of two and three thousand feet during the Pleistocene, I may say, in passing, the answer is quite firmly that this is not possible when viewed from these biologic viewpoints.

MR. LONGWELL A suggestion made to the Geological Society recently seems to have considerable merit. It had to do with the Atlantic ridge. If we can study some parts of that ridge—fairly shallow parts well removed from any islands—by means of the sonic depth finder and these other modern tools, and find there some submarine canyons, heading east and west, that would have a very strong bearing on this question of lowering the sea level. You could not very well call on Daly's density currents to explain such canyons in that position, but if the sea has been lowered several thousand feet it is very conceivable that such canyons have been cut Of course, their absence might not mean anything one way or the other, but their presence would be very suggestive.

MR FIELD I might say, in reply to Mr Longwell, that certain British geophysicists and geologists are interested in such an expedition, and that plans are being discussed with the British Navy for such an exploration of the Atlantic Ridge

THE CHAIRMAN. Mr Dickerson is an oil geologist and oil geologists have done a lot of work in gravimetry and seismology Does he have anything to say?

MR DICKERSON Mr Chairman, I merely want to ask concerning the possibility of using Dr. Fleming's device for direct measuring of cores from land holes Could you get any variation in magnetic effect between the bottom of a six-thousand-foot hole and a core taken up about a thousand feet? In other words, is there any difference in the magnetic effect in the core in the Pliocene compared to a core in the Upper Cretaceous?

MR FLEMING. Nothing has been done in that line yet, but I think we would very much like to do it

MR. ECKHARDT· I have been engaged in geophysical work in the oil industry and I am impressed this afternoon with the differences in viewpoint It is very much like this. It seems to me that this broad viewpoint of geophysics which we have been hearing about this afternoon is like being in a region where the trees are so far apart you cannot see any two at the same time, whereas in the case of applied geophysics, you are in the middle of a little spot where there are so many trees you cannot see out.

I think this symposium has been extremely valuable It typifies an effort to get at some real data instead of the vast amount of speculation which has been indulged in in the past, and I believe that it should be encouraged I think the Philosophical Society is to be congratulated in having fostered an opportunity of this kind

MR HECK I would like to call attention to something Mr Hess said about gravity anomalies On the south side of the Caribbean is the only place I know where these marked anomalies do not parallel, at least approximately, earthquake belts The earthquake belt extends from Trinidad southwest toward Southern Colombia, following the main Andes but the anomalies follow along the edge of the Caribbean

MR VAUGHAN Mr Heck has shown you these charts A few years ago the International Hydrographic Bureau, although it had the facilities for publishing the charts, did not have the money for hiring draftsmen The Philosophical Society made a very substantial contribution to pay a draftsman for putting together these charts

MR THOM In discussions of the cutting of the suboceanic canyons and river valleys, disclosed by recent geodetic-geophysical surveys, it has been variously suggested that this cutting was made possible by the temporary lowering of sea level of as much as 12,000 feet By some this lowering has been pictured as having occurred in certain latitudes only, whereas others have postulated that it was similarly effective over all oceanic areas

Having had occasion to work in high-plateau areas, and having noted various features characteristic of such plateaus, I should like to ask any meteorologists present whether a regional lowering of sea level by ten or twelve thousand feet would not have caused profound climatic changes in the continental regions—changes so profound as to have left enduring and unmistakable evidence of their occurrence, both in the life-records and physical features of the land areas?

It seems to me that the assumption of any general lowering of such an extent can, for several reasons, be regarded as one of very doubtful probability—even though the fact that sea level has fallen *relatively*, and at least locally, seems amply demonstrated by the submarine erosional features now known to exist By what process the cutting of the suboceanic canyons was made possible we can guess,—but without additional limiting facts we shall perforce continue to guess, without appreciable scientific advance or advantage

Mr Chairman Suppose the sea level should drop twelve thousand feet—what would be the effect on the climate of North America?

Mr Humphreys It would be such as it now is on the very highest plateaus of Asia, more or less arid because of the fact that precipitation would occur chiefly at much lower levels Not much water vapor could get up to that great height, but from it there would gradually accumulate, I fancy, a great deal of snow and ice I think the Antarctic and Greenland answer the question

Mr Thom Mr Chairman, as a structural geologist, I have been especially interested in this afternoon's symposium because of its demonstration that ways are now open for notable advances in my field of scientific interest Students of structural geology have long been accumulating factual data bearing upon the three-dimensional form, space-pattern, and time relationships of the deformational crustal features of the continental areas—and great advances have been made in these studies—but each time workers in the structural field have sought to make an analysis of facts in hand such as should disclose the causes and *modus operandi* of crustal deformation, they have arrived at several conflicting and more or less equally plausible hypotheses, and have found that the needed decisive evidence was beyond reach—because it must be sought in the then-inaccessible suboceanic regions Consequently, I feel that great importance attaches to the demonstration that the combined use of geological and geophysical-geodetic methods now makes it possible to carry continuous exploratory traverses from the continental highlands to the oceans' depths—thereby revealing, among other things, the morphology of the sea floor, the true nature of continental margins, the presence or absence of "continental type" rocks in sub-oceanic areas, the form and extent of past and present geosynclines, and the possible existence of submerged portions of mountain systems—as, for instance, in the North Atlantic between the Appalachians and their apparent continuations in northwestern Europe

I have no doubt that workers in many other fields are similarly elated that the developing geophysical exploratory techniques are opening such extensive and important new areas of investigation And I feel confident that we shall, within a few years, make great progress in substituting fact for theory in many important scientific directions In order to obtain the great amount of new data needed, a comprehensive program of cooperative work will obviously be called for—especially since the problems involved transcend the capacities of the agencies of any one country. However, that the necessary facilities can be obtained, seems reasonably certain, both because of the broad general interest of the problems under attack, and also because of their major scientific importance.

THE CHAIRMAN I would like to ask questions of Dr. Piggot. These ten-foot cores would represent sediments of about two hundred and fifty thousand years.—It seems to me Dr. Schlundt, out in the Yellowstone Park, had a pretty good measure of age by the decay of radio-activity Do you suppose you could apply that method to these ten-foot cores?

MR PIGGOT We were hoping we could. It is a difficult job because we cannot get as much radium as we would like out of the cores There would be a chance to go through greater time intervals on top of the mid-Atlantic ridge. There may be other places where stratification has been so slow that cores would give you a longer record I was able to make only one shot on the ridge, but if I had been able to control the ship at that place—or control the authorities on the ship—I would have stayed there till I got a ten-foot core at that spot by sending down more energy. I don't know whether this material would give you the information you want, but it would represent a much longer period If you lengthen the bit to fifteen feet and cut through more sediments ten or a hundred times slower in forming, which we hope to do, it would increase that age stretch considerably

MR. FIELD. I would like to ask Dr Piggot whether he thinks it is going to be possible to get down to great depths, and what will be the ultimate limit of length of cores that he will be able to get in oceanic depths?

MR. PIGGOT We started with a five-foot core, moved to six, then ten, now we are trying to build apparatus that will get a fifteen-foot one We are building a winch with 5400 fathoms of line on it, using tapered cable

MR HECK I would like to mention a subject of which nothing has been said, namely, the very marked achievement of carrying explosion methods into these great depths As far as I know, neither explosive technicians nor military authorities attempted this before this work Mr. Piggot has gone to depths of 2500 fathoms, and has planned to go to 4000 or 5000 What is the pressure at that depth?

MR PIGGOT· Five thousand fathoms—that is fifteen thousand pounds per square inch. Our greatest depth to date has been just a little under 3000 fathoms

MR HECK I think we ought to recognize that this achievement is partly due to activities of the Naval service and such organizations as duPont's, and I understand their officials have been very coöperative in helping work out these problems.

MR. PIGGOT I would like to add to that remark that I do not think my apparatus would have gotten anywhere at all if it had not been for the aid of Dr. Mackey, of the Burnside Laboratory of the duPont Company—their powder research laboratory—and Dr Dew and Mr. Lloyd, who have worked on that They were very enthusiastic in their coöperation and made absolutely fundamental suggestions

MR. EWING: I would like to add to Mr Piggot's remarks about the coöperation from the duPont people. When we started out to make seismic measurements in 2600 fathoms during the past summer, I had not had any experience trying to fire high-explosive in such deep water We had pressures in our work of about eight thousand pounds per square inch and our problem was very different from Dr. Piggot's He wanted one kind of explosion—a sort of push, we wanted an explosion to disintegrate gun, apparatus and all, within as large a radius as possible, and frankly I doubt if I would have had one bomb go off, up-to-date, if I had not got some very excellent help from this same organization

MR SMITH Mr Dickerson's and Mr. Thom's remarks suggested that so far as is known we have not definitely found the seaward extremity of any of these canyons in any surveys the Coast and Geodetic Survey has made We have traced some of them on the Atlantic coast to about 1650 fathoms depth, about 150 miles offshore They are still evident, although the gradients decrease, and in one case on the Pacific coast, off Point Sur in California, there is pretty good evidence that what looks like the extension of the Upper Big Sur River on land continues under the sea for about 125 miles winding about a submarine mountain which stands 7000 feet from the floor of the ocean in depths of 2000 fathoms (12000 feet) That even stretches the limit of this postulated lowering of the sea beyond the wildest dream, if these submarine valleys are to be accounted for in that manner.

There is something else that Mr. Dickerson might be glad to know, and that is that the Cagayan River on the north coast of Luzon is one of the few that carries its submerged channel directly through the continental shelf The Congo is another A few others have been found to have their submarine channels running through the coastal shelf. Most of them have been obliterated at the coastal shelf. This applies particularly to the regions we have surveyed accurately by modern methods

THE CHAIRMAN I would like to ask Mr. Longwell or Mr Smith of the U S Coast and Geodetic Survey whether some one had not asked the Project's Committee of the

Geological Society of America for a grant to explore one of these canyons

Mr. Smith I have been working with Dr Veatch in contouring the charts from recent surveys off the Atlantic coast, and there are so many things coming out of the work I hesitate to comment on them at the present time except to say that there are a whole lot of facts that are most interesting, but before commenting we would like to give them more study

Mr Hobbs I wonder why it is necessary to give the discussion the peculiar turn it has taken? Why do we assume when we find certain fissures—sub-aerial fissures—beneath the sea, that there has been a lowering of the level of the sea, when it is so much easier to lift the bottom of the sea up, and it has been only the French who have taken this view to any extent? Why do we have to assume withdrawal of the water from the ocean when the other is a much simpler assumption? Nowadays we move continents—according to some authorities—as if they were ships at sea, yet we cannot accept the idea of vertical movements of the ocean bottom while the evidence is about us

Mr Dickerson In reply to Mr Smith, I wish to call attention to one notable Pleistocene river which has received very great study upon the part of the Dutch The Molengraaf River rose in Sumatra, and formerly flowed north between Borneo and the Malay Peninsula for a distance of 1200 miles I do not want to introduce at this time a fish story, but it is quite necessary The fish fauna in this basin have been exceedingly well studied—the fresh water fish in particular. The fresh water fish fauna of South Sumatra, Borneo and Indo-China are essentially the same There are something like forty or fifty per cent of the species in common to those now widely separated regions. The Dutch not only studied it from this point of view, but they have shown that in the great now-drowned plain between the Malay Peninsula and Borneo, a distance of about four hundred miles, you can anchor a ship anywhere in two hundred feet or less of water.

Not only that, but the South Palembang peneplain in South Sumatra slopes northward into the Molengraaf River and all the streams of the South Palembang peneplain of Pliocene age turned northward. Part of the tin mines—placer tin—are in one of these streams. In the Island of Banka the tin gravels are in one of these old Pleistocene tributaries of Molengraaf River. We may trace northward this river by means of a fish tale! Dr. Herry, now at Stanford University, made a study in the Philippines, on the Island of Palawan, and found that the residual fish fauna was Bornean, so that the Molengraaf River emptied somewhere in the China Sea off Manila.

Mr. Bowie Mr Chairman, this really has been a cheerful and helpful meeting. Some of us who have been working in the field of geophysics for many years have wondered at the slowness with which the geologists have employed mathematics, physics, chemistry and mechanics in attacks on some of their baffling problems

It is very seldom that students in dynamics and structural geology agree The reason for this would seem to be that they have not used enough geophysical technique to get the data that they should have in order to interpret what has really gone on in the earth, and what is likely to happen in the future Since the geophysicists and geologists have developed instruments, methods, and techniques, it seems to me the time has come to bring into the picture all agencies that are interested in the use of data secured to solve economic problems

I should like to ask this question How are we going to do much in geodesy, geophysics, geology, and the interpretation of the data that may be collected, unless we have complete knowledge of the configuration of the earth's surface? There are only a few areas where there are good topographic maps (mostly in Europe), and those maps were made not for scientific or industrial purposes, but for war purposes.

In the United States not over twenty-five per cent of our three million of square miles of area have topographical maps that are suitable for modern uses Forty-seven per cent of our area has topographic maps, but half of them are of the reconnaissance type, and are of little value to the scientist, the engineer, the geologist, or others. We are spending large sums yearly on all kinds of conservation projects in the absence of adequate maps. No doubt much of that money is wasted

If many of the naval vessels of the world could be assigned to a survey of the oceans, it would only require a few years' work to give us charts that would be invaluable in the attack on some of the problems that have been outlined here today. I think we ought to get some real facts on the topography of the ocean bottom and better maps of the land, then we would be able to make great advances in the fields of geology and geophysics.

MR HUMPHREYS May I sow just one or two seeds here? I tried them on the Geophysical Union but the soil was barren. I will try it here based on these promises that we are going to have help from the Navy and elsewhere. It is this: Why do we not know much more about the rate at which water that came on to the land in the form of ice and snow is now going off in the form of water? There certainly have been some changes in the amount of this ice in the past, we have had glaciation and deglaciation They tell us we are still in the latter part of the Ice Age—and that the glaciers are retreating and have been retreating for a long while; nobody agrees as to the length of time involved.

What I want to know is what is happening now and what is going to happen a little later on I have got so I am not interested in the past any more, but what is happening right now, and what will it lead to?

I think there is a way—certainly there would be if the earth would quit squirming—to find out to what extent it is going one way or the other I am assuming now that the earth is not wiggle-waggling, going up and down, heaving and puffing and so on, but staying put. The place it is most likely to stay put is in the tropical regions not so far from the Equator On a number of islands, let us put down wells, connecting with the ocean with sufficient damping action so that the height of the water in the wells will not be affected by the tides, and equipped with suitable recording devices that will keep track of the level of that water year in and year out If the glaciers are now melting at the rate they apparently have been going during the last ten or twenty thousand years, the change in sea level would be in the neighborhood of one-twelfth of an inch a year, provided the earth is not wiggle-waggling I would like to see a number of such stations as these.

Of what use, do you say? If deglaciation continues at this rate, in a few thousand years the United States will be a dust bowl, if climatic conditions remain what they have been Since storms necessarily follow in general around cold borders, when the ice came down over Europe to a considerable extent storms followed a more southerly course, the Mediterranean and North African regions were well watered As the ice retreated toward the north, so too did the storm track, and the regions abandoned by storms became dryer It would be much the same way here, as the ice would go further and further north the storms in general would be at higher and higher latitudes.

This proposal of wells is a perfectly simple one They can be established on a number of suitable islands and by comparison with one another or by allowing each to keep its own record for ten, fifteen, or twenty-five years, we can observe the relation of this retreat of the ice to the rise of ocean level This is based on the assumption that these islands are not going up and down

MR BOWIE Of course, we have the tidal stations all over the world I do not see why we cannot depend upon these. Take hourly readings year in and year out and the average cannot be more than a millimeter one way or the other from the actual mean sea level Of course, if there are storms they cause abnormal tides, but in general the average of the hourly heights is close to the true mean sea level for a station.

At any rate, I do not see why Mr Humphreys and Mr Whitney should not get together on that in Washington and report here next year

Mr Humphreys We have tried that and found it is difficult The point is to have such damping that there is no response even to the lunar tides through the months, to have small tubes feeding into rather large basins which will not be appreciably affected in level by these tidal fluctuations, only by slow annual changes

Mr. Bowie Mr Chairman, the Coast and Geodetic Survey found wells a hundred yards back from the sea near Atlantic City having tides in them corresponding very closely to the tides of the ocean, except that the range is not so great

Mr Vaughan Also, you could not get rid of ground water effects

Mr Heck In southeastern Alaska, there is a good deal of evidence of rise of coast line of three feet in twenty-five years, and it is still going on.

Mr. Bowie The coast of southern Sweden is going up a foot or two a century According to Nansen and others, that is simply coming back after the release of load by the melting ice.

Mr Humphreys Mr Chairman, it is these blessed seismologists—I don't mean seismologists, but isostasists that confuse the problem I take it if the earth would quit squirming, going down at one place in response to load, the thing could be measured, but if the earth is going to behave according to the way the isostasists want it to behave, of course, calculations are all out

Mr Bowie· Mr Chairman, I want to tell you the isostatic and geodetic earth wants to stay still, but the meterorologists give us evaporation, erosion, sedimentation, unloading some areas and loading up others The equilibrium is disturbed, and then we poor geodesists have to get it back again, and then the meteorologists come and upset it again I do not know what we are going to do about it unless we eliminate the meteorologists.

Mr Russell Has anything been done yet to find out what the gravity anomalies are on the big deep opposite the west coast of South America along the Andes?

Mr Bowie We haven't done any work in that area, but really it would be most interesting. We have a few gravity stations over the deep to the west of Mexico, and I should like to make a comment about the gravity anomalies because some of you may get the idea the old earth is really in terrible shape on account of these little narrow belts of negative gravity anomalies. First, let me tell you that these anomalies are the outstanding unexplained differences between the theoretical and the observed values of gravity after applying all necessary corrections The anomaly is a measure of the extent to which the isostatic conditions that are postulated do not exist But these belts are very narrow—thirty or forty miles wide—or something of the sort—and usually alongside the negative anomalies there are positive ones. So the area as a whole—West Indies and East Indies as a whole—is practically in perfect isostatic equilibrium. How small a block would be independently in equilibrium I do not know It may be fifty, one, or two hundred miles square There is no such thing as these areas being ready to collapse, either popping up in the air thousands of feet or being depressed an equal amount. We have got some local phenomena in the regions of the East and West Indies, and Meinesz and Hess might be on the right track in postulating that weak material or material of low density is folded down to account for the great negative anomaly belt

Mr. Field Mr. Chairman, I wonder if Mr. Ewing or Mr Hess would care to say anything about the advisability of gravity determinations on the Andes, south of Panama?

Mr Hess The negative anomaly belt in the Caribbean apparently enters the north coast of Colombia; probably it once followed the Cordilleran Central. It may well emerge again in the ocean south of Peru, thus the vicinity of the great deep off South America, in this region, is worth investigating.

Mr. Field: Also, there is probably more sedimentation going on in the Peruvian coastal deep than in the East Indian and West Indian deeps

The Chairman I wonder if the oil companies investigating the region around Lake Maracaibo could contribute to our knowledge on this subject.

Mr Eckhardt There is a great deal of oil work in Venezuela, but it has not been extended across the mountains The eastern Venezuelan basin has been pretty well surveyed and those gravity data are available.

The Chairman But your negative belt is not on the mountain range proper?

Mr. Hess It is at sea north of the mouth of Lake Maracaibo It might be picked up further east—just west of Trinidad, in Venezuela, if gravity work were done there.

Mr. Bowie · I would like to pay tribute to Mr Eckhardt. His company has made gravity observations at probably five thousand or so stations in Louisiana, Texas, and other places, and he has furnished to the Coast and Geodetic Survey, data for some seventy or eighty of his stations I do not know whether they have been reduced yet They will be as soon as men are available for the work, then the data can be made public, and it will give us very closely spaced stations in that region—I think the stations were mostly in Texas

Mr Ewing I hate to ask Mr Eckhardt for many more favors since I have asked him to get me out of jams in connection with apparatus we used last summer, but I would like to ask where these gravity data are available for northern South America.

Mr. Eckhardt · We have them in our files. I do not mean they have been published, but it would be difficult to correlate our gravity figures with yours. We have an arbitrary starting point down there, and as far as I know there are no gravity stations within the entire area that would tie in with your marine gravity data. If you can make that correlation or induce Dr. Meinesz to do it, I am sure we would be very glad to supply any data we have.

Mr Garner While on the subject of gravity observations I thought the meeting might be interested in Dr. Lopez, of Venezuela, who requested the coöperation of the Coast and Geodetic Survey on the gravity observations down there this winter It is entirely out of the question to attempt it now and entirely too early to predict what can be done in the future, but an expedition is being planned for next winter

The Chairman Are there any further remarks? If not, the discussion is closed

MODERN DYNAMICAL OCEANOGRAPHY: AN ACHIEVEMENT OF APPLICATIONS TO OCEAN OBSERVATIONS OF PRINCIPLES OF MECHANICS AND HEAT

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ABSTRACT

This paper begins with a general historical review of researches on oceanic circulation conducted since the introduction, in the early part of the nineteenth century, of Lt Maury's international cooperative plan of making and reporting ocean observations The treatment throughout is non mathematical and an attempt is made to furnish the reader who is not a specialist in the field with a comprehensive survey of progress already made and of problems to be solved Both theoretical methods of calculating ocean currents from observations of wind, temperature and salinity, and observational methods of determining ocean currents are considered Special attention is given to errors made in earlier attempts to apply to the ocean theories based upon laboratory experiments Revisions of these earlier methods and the rapid developments leading to the more satisfactory modern ones are briefly outlined

Then, following an introductory classification of the various forces that generate and maintain oceanic circulation there are general outlines of various methods of applying the principles of physical hydrodynamics to problems of oceanic circulation There is also an elaboration of the theory of eddy viscosity and turbulence which processes account for rapid diffusion of momentum, heat and chemical properties Next a method is explained of calculating the circulation that would account for the departure of actual surface temperatures from their normal values

The explanations mentioned above are restricted to the fundamental part of the mathematical-physical treatment of oceanographic problems involving only the simplest conditions and essential methods The paper concludes with a supplementary discussion of revisions made necessary by a more detailed consideration of actual conditions such as nearness to coastal boundaries and irregularities in depth

INTRODUCTORY STATEMENT

In line with the trend in science an industry toward cooperation between specialists for the purpose of offsetting the limitations inherent in specialization, the preparation of a series of bulletins dealing with geophysics was proposed by the Division of Physical Sciences of the National Research Council As a result of the efforts of a large committee of investigators appointed to carry out this undertaking, 9 volumes have been published. This paper is a brief general statement based upon the chapter on Modern Dynamical Oceanography written by McEwen for Physics of the Earth—V, Oceanography (Bulletin No. 85).

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[1] Contribution No 11 from the Scripps Institution of Oceanography, La Jolla, California.

GENERAL HISTORICAL REVIEW

Lt Mathew Fontaine Maury of the U. S Navy initiated and developed an international cooperative arrangement for making observations at sea and reporting them on standard forms These records are sent to various central offices where compilations are made and charts are prepared to provide navigators with information in convenient form relative to winds, currents, and temperatures.

Maury's *Physical Geography of the Sea,* published in 1855, was the first textbook or treatise on Physical Oceanography. It was a logical outgrowth of the international program of observations This pioneer undertaking was followed by great improvements in observational technique, yielding results of high precision, and by the evolution of methods of handling oceanographic observations from early qualitative, descriptive types into a more rigid and quantitative treatment of oceanic phenomena according to the laws of physics. Since the turning point of 1875, marked by James Croll's critical book, *Climate and Time,* dynamical oceanography has progressed at an increasing rate, as indicated by the numerous important papers and the growing list of investigators. All of this progress is intimately connected with the names of Helland-Hansen, V. Bjerknes and V. W Eckman, whose basic contributions to dynamical oceanography began to appear at the close of the 19th century. During the period since 1900, the great accumulation of observations and the development of more careful reasoning and quantitative treatment of questions pertaining to the solid earth, its atmosphere, and its oceans, led to greater specialization in the various fields of geophysics, including that of physical oceanography.

Observations without the use of instruments can, in general, reveal but little information concerning ocean surface currents, and nothing about subsurface currents Direct observations of currents with the aid of floats or current meters require conditions rarely met with in the high seas. For observations even on surface currents we are dependent mainly upon indirect means, such mechanical ones for example as drift bottles set adrift at known positions and times and the departure of ships from their apparent courses. Current measurements are, in general, far from being as precise as observations of other physical phenomena of the ocean water The most accurate current measurements have been made in shallow inshore waters and, on rare occasions, in deeper waters from specially equipped ships at anchor. As evidence of progress in instrumental equipment attention is called to a late type of current meter designed to rest upon the sea bottom and to record the rate and direction over a period of days. Thus it is now possible to make an intensive current survey of limited regions.

However precise and complete oceanic observations may be, merely making and compiling them is but the first step in the investigation of the ocean. It is only by attempting to coördinate and interpret objective knowledge that we can realize an adequate return from such efforts This demands the definite formulation and solution of certain special problems suggested by oceanic and other cosmical data with a view to discovering causal relationships between the various phenomena and to showing their harmony with general principles already established by investigations in other fields. Thus by obtaining a series of definite and proved relations, each relation involving two or more types of physical and chemical magnitudes, and by synthesizing these elementary results, we approach the ideal of a system of general laws of the sea, based upon objective knowledge.

In this way we can describe the many diverse phenomena in terms of relatively few and simple fundamental ones. Moreover, attempts to formulate theories of oceanic circulation are no less necessary than observations, even as means of ascertaining the facts about such obscure and complex phenomena.

Biologists, geographers, and geologists have carried on many investigations in physical oceanography, but only incidentally to work on the problems of special interest to them. Accordingly, qualitative and descriptive methods, formerly so characteristic of the sciences of biology, geography, and geology, have been widely used in oceanographic investigations. Such methods and the empirical treatment of quantitative field observations have been very suggestive, have stimulated interest, and have led to certain broad generalizations that are essentially correct, but an early tendency toward rather loose reasoning and lack of consideration of established quantitative principles of physics, resulted in certain erroneous conclusions. Even after both laboratory and mathematical physics were well advanced, inherent difficulties and the incompleteness of field data led the pioneer investigators to varied and conflicting conclusions.

Must we admit that our lack of control and the complexity of such geophysical phenomena render careful reasoning and quantitative treatment impossible of attainment? Although such an achievement may at first appear unattainable let us give the matter due consideration before expressing an opinion. Especially since Croll's contention in 1875 of the necessity of quantitative reasoning in this field, a few scientists have undertaken, by means of a definite formulation of specific problems, to apply mathematics to quantitative ocean data, and thus to contribute to a system of demonstrable principles applicable in general to all similar cases. Such work is essential in developing a science of the sea. Important advances have thus been made and serious errors in certain former conclusions have been discovered, although in some of the earlier attempts at mathematical applications, significant errors arose from incorrect assumptions and the failure to appreciate characteristics peculiar to such "field" or natural problems At first, scientists accustomed to problems of laboratory physics attempted to deduce physical laws of the sea from results of laboratory studies and from certain preconceived assumption regarding oceanic conditions Furthermore, they worked under the disadvantage of having very inadequate data As more accurate and exhaustive data accumulated, greater attention was directed to interpreting and coordinating field observations than to imposing on the sea purely theoretical laws deduced from laboratory researches

Prior to 1845, when Professor A. D Bache, who was then director of the United States Coast Survey, formulated the first systematic plans for investigating currents in the Atlantic and used a vessel equipped especially for that purpose, investigations of ocean currents were merely adjuncts to other work Actual measurements by means of current meters were first successfully carried out within the modern period and were necessarily restricted to special working conditions Such measurements and records based upon especially constructed floats have resulted in a detailed knowledge of currents unattainable by the earlier methods alone

Returning to attempts to deduce laws of oceanic circulation, the German physicist, Zoppritz, was the first to appreciate the importance of the viscosity or internal friction of water in investigations of ocean currents Before 1878, when he published the first mathematical theory of wind-driven currents, the opinion prevailed that a difference of level was necessary for the production of a current It was still believed, as stated by Varenius in the seventeenth century, that "water has no natural motion except that which follows when it flows to lower levels" But Zoppritz concluded, from the theory of a viscous fluid, that the wind could produce a surface current by its friction on the water surface. This upper layer would, in turn, move water underneath, and thus in the course of time give rise to motion throughout the whole body of water between the surface and bottom In agreement with this, the idea that winds can produce a current by the horizontal force of friction on the surface has always been held by practical seamen They have always regarded the wind as the main cause of all currents in the open ocean that have an appreciable influence on the navigation of ships. However, when suitable measurements of currents were available, it was found that the results of Zoppritz's theory involving laboratory values of the coefficient of viscosity were of an entirely different order of magnitude from the observed values. Thus the elaborate theory that he developed, although mathematically sound and widely accepted and applied by other investigators, proved defective in practical applications Yet his work was of value in stimulating further researches and in removing objections previously raised against the theory of wind-driven currents

Bjorknes and Ekman abandoned the concepts peculiar to *Classical hydrodynamics* for those of *Physical hydrodynamics* The fundamental assumptions in classical hydrodynamics are · first, flow is either in practically parallel layers as demanded by the idea of viscosity dependent upon laboratory experiments, or fluid friction is neglected; second, the fluid is *barotropic*, that is, it is either homogeneous and incompressible or the density varies only with the pressure In the atmosphere and the ocean the density varies with factors other than pressure; temperature and humidity influence the density of the air, and the density of sea water depends upon temperature and salinity Moreover, neither the sea nor the atmosphere can be regarded as fluids flowing only in parallel layers as in the case of controlled laboratory experiments on viscosity. Both have a great apparent viscosity because eddies, characteristic of ocean currents and winds, transfer particles of the fluid across the boundaries between layers along which the average flow proceeds. Accordingly, laws valid for the ideal fluid of classical hydrodynamics are not adequate for the treatment of problems of the motion of the sea or atmosphere. Professor V. Bjerknes, as a result of collaboration with his father, continued his investigations of fluid motion and founded the science of *physical hydrodynamics* in which the fluid is regarded as *baroclinic,* that is, the density depends not only upon pressure but upon other factors such as temperature, salinity and humidity He realized that when we cease to consider problems of classical hydrodynamics as special cases of more general hydrodynamical problems, we shall often find new, more fruitful, and general methods of dealing with them As a matter of fact, in classical hydrodynamics the problems are mainly defined by the surface conditions, while in physical hydrodynamics the necessary conditions are contained in the fundamental equations themselves. Thus the way is prepared for practical generalized methods His student, V. W Ekman, devoted special attention to the concept of eddy motion or turbulence and its consequences, and is the first one to include in a rigorous mathematical treatment all of the factors essential to wind-driven currents

Later contributions of Bjerknes, Ekman, and other investigators inspired by the new viewpoint are widely scattered in many special publications The need of making these modern results more accessible to students of oceanography is accordingly urgent. For the only adequate attempt to meet this need we are indebted to Dr. Albert Defant, whose book *Dynamische Ozeanographie,* 1929, published in German, presents a connected treatment of the fundamental concepts upon which the modern study of oceanic circulation is based. A glance through this book indicates the extensive use of the methods of mathematical physics that prevails in modern dynamical oceanography. A careful study indicates how well the author has succeeded in unifying the whole subject and in explaining the physical significance of every step in the calculations.

The mathematical-physical treatment of oceanographic problems included in dynamical oceanography may be divided into two parts. First, there is the fundamental part involving the simplest conditions and essential methods. Second, there are modifications of such simple results which are made necessary because of variations in actual conditions, *e g*, irregularities in depth Thus it is possible to provide a sufficiently close connection between ideal problems, essential to any quantitative investigations in oceanography, and actual problems

It has formerly been necessary to use as a basis for theoretical work such scattered data as the investigator could find. Much has been, and doubtless will be, accomplished in that way But such a procedure has obvious disadvantages, such as insufficient or unknown precision, incomplete data, or lack of significant factors that may impair or greatly restrict the conclusions. Therefore, it is also necessary to conduct special programs of intensive observation, designed with reference to particular problems, in order to improve and supplement the above more extensive and preliminary type of work. Thus, selection of conditions such as locality or season, and the attempt to observe all relevant phenomena, may afford advantages approaching those of the laboratory physicist who controls the conditions affecting his experiments For example, serial temperatures observed in the relatively quiet and deep central part of a high-pressure area, undisturbed by land boundaries, provide results corresponding to the simplest conditions and would be of great aid in the study of "normal" temperature gradients Such observations should also be accompanied by observations on the intensity of solar radiation, turbidity, salinity, and evaporation, and should be continued through different seasons and times of day in order to provide the most important kinds of data. Very little of this intensive type of work, carried on with sufficient continuity and completeness, has been done and it has been restricted to certain portions of small inland seas or inshore regions. Although results thus obtained are valuable in themselves and as a means of interpreting such fragmentary and widely distributed data as may be available, they cannot take the place of similar intensive work at selected stations throughout the ocean Actual conditions in typical areas of the great oceans must be carefully observed and studied if any reasonable approach to exhaustive oceanographic investigations is to be realized

Purely empirical or statistical methods are indispensable in assembling and coordinating various kinds of field data. However, progress from such empirical results toward the ideal of a deductive treatment carried out in accordance with known generalizations of physics is also necessary. Some of the methods of carrying out such investigations will now be briefly outlined.

THE FORCES THAT GENERATE AND MAINTAIN OCEANIC CIRCULATION

Various forces generate and maintain the motion of the sea For convenience, they are divided into two groups, *internal* and *external* forces.

Internal forces arise from gravity and the distribution of mass within the sea and are therefore intimately related to its physical constitution which depends upon temperature and salinity Accordingly, the internal forces are modified by the gain or loss of heat due to radiation, conduction, convection, and evaporation. The addition of fresh water or its removal by evaporation also modifies the internal forces by changing the salinity and the temperature.

External forces include the effect of winds on the sea surface, changes in atmospheric pressure, and the tide-generating force of the sun and moon These forces cannot directly alter the physical character of the water but may, through the resulting motion, change the distribution of mass and thus disturb the internal system of forces

In addition to these two groups of *primary* forces there are two *secondary* forces, the deflecting force due to the earth's rotation and the frictional force at the boundaries between water masses moving with different velocities The first acts at right angles to the motion, to the right of an observer facing in the direction of motion in the northern hemisphere, and to the left of the observer in the southern hemisphere The second, or internal friction, acts along the line of motion in such a way as to retard the relative motion Neither of these secondary forces can of itself generate motion. Although both are consequences of motion already generated they exert such an important influence on the circulation as completely to transform it

THE BJERKNES CIRCULATION THEORY

The principles of mechanics embodied in Newton's three laws of the motion of a "particle" apply fundamentally to a continuous medium, for example, to a fluid But in order to investigate fluid motion these principles must be expressed in an appropriate form and the medium must be suitably described.

In 1885 the Norwegian meteorologist, Mohn, estimated the height of the surface of the Norwegian sea at a network of stations by means of serial observations of temperature and salinity He called this the "density-surface" since its elevation relative to a level surface depends upon the distribution of density Assuming the current due to the wind to be proportional to the wind velocity and in the direction of the wind, he estimated the shape of the "wind-surface" or surface of the sea necessary to provide a pressure gradient at right angles to the current sufficient to balance the deflecting surface due to the earth's rotation Adding to this the departures from the mean level of the "density-surface," he obtained the "current-surface" from which the actual current was estimated by using the principle that the deflecting force due to the current balances the force due to the pressure-gradient. Mohn was a meteorologist rather than a mathematician or laboratory physicist, but was convinced of the necessity of applying quantitative methods in hydrography. His pioneer achievement marks the beginning of a new era in the investigation of ocean currents, and it contributed much toward the development of the more satisfactory modern methods

The fundamental work of V Bjerknes in physical hydrodynamics served as a basis for the development by him and his students and colleagues, Sandstrom, Nansen, Ekman, Helland-Hansen, Sverdrup, and others interested in physical oceanography, of modern practical methods for computing the direction and velocity of ocean currents from serial temperatures and salinities at a network of stations.

The simplest and most commonly used special case of the Bjerknes circulation theorem assumes a fully developed current caused by the distribution of pressure corresponding to the observed distribution of temperature and salinity. A convenient plan for computation has been devised for obtaining the dynamic depth of any point The dynamic depth equals the work done against gravity in raising a unit mass from that point to the sea surface and is inversely proportional to the density of the water The deflecting force at a given latitude due to the earth's rotation is proportional to the velocity of the water and must balance the pressure gradient which is proportional to the difference in "dynamic-depth" between the boundaries of the current. In general, his formula expressing these relations serves to calculate the horizontal current at one level relative to that at another level.

Eddy-Viscosity and Turbulence

In the motion of the atmosphere and the sea, instantaneous velocities in the numerous eddies are unknown, only the average velocities are observed or considered in detail In 1894 Osborne Reynolds demonstrated that in all such cases the coefficient of viscosity must be replaced by the coefficient of eddy-viscosity in order to harmonize theory and observations. The coefficient of eddy-viscosity or virtual viscosity for the atmosphere is of the order 3×10^5 times the laboratory value for air. For the sea the ratio is of the order 0.2×10^5. Both ratios vary widely with conditions. These great differences between the virtual viscosity and its laboratory value are due to the fact that we do not observe the actual motion in all of its details. Our instruments furnish only mean values averaged over an interval of time and space, while the actual motion is turbulent. Thus turbulent or mixing motion causes an interchange of energy, of motion, and of other properties between the separate fluid layers. In consequence there is a very great apparent viscosity as long as one follows the motion only macroscopically.

Ten years before Taylor, Richardson, and Schmidt published their first papers dealing with turbulence, Ekman recognized and made use of this principle in his pioneer investigations of wind-driven currents. He is the first one to include in a rigorous mathematical treatment all of the factors essential to oceanic circulation that is caused by wind. These factors are the frictional drag of the wind upon the water surface, the deflecting force due to the earth's rotation, and the internal friction due to relative motion within the water. Under certain conditions that are often realized in practice when applying the Bjerknes theory, the internal friction is of little importance and may be neglected. But in wind-driven ocean currents it is always fundamental, and is due to irregular eddies involving an interchange of the position of small masses of water. Turbulence or eddy motion may be measured by the mass of fluid exchanged per unit time per unit area between two neighboring units of volume. This quantity has been called "die Austauschgrosse" by W. Schmidt, and the eddy-viscosity by L. F. Richardson and G. I. Taylor in their investigations of the dynamics of the atmosphere.

Turbulence is important not only in the phenomena of winds and ocean currents as indicated above, but it has a much wider significance because of the nature of the eddies An eddy may be defined as a portion of a fluid that moves from a stratum where it has the same physical and chemical properties, *i.e*, temperature, humidity, salinity, etc., as the fluid surrounding it, to another stratum with which it mixes. Thus, turbulence is the mechanism of heat conduction and diffusion of substances mixed with the atmosphere or the water It endows a fluid with the ability to transmit heat as readily as a solid having a very large coefficient of conductivity. Likewise a turbulent fluid transmits dissolved substances as readily as an undisturbed one having a very large coefficient of diffusion The stratification of sea water in layers of increasing density from the surface downward is a fundamental factor tending to prevent mixture or reduce turbulence in proportion to the vertical density gradient

The assumption of a constant value of the turbulence from surface to the bottom often departs widely from actual conditions. Accordingly each of a series of smaller intervals, within which the turbulence is approximately constant, may be considered separately Important contributions toward the theory of this more general case and towards the correspondingly complex mathematical procedure have been made by several investigators, notably, V W. Ekman, J. E Fjeldstad, K Hidaka, H Arakawa and C. G. Rossby Furthermore, important work involving turbulence has been done by G Wust, R Cherubim, H U Sverdrup and others in the Zone of Contact between the sea and air, and between the ground and the air.

THE EKMAN THEORY OF OCEANIC CIRCULATION

Ekman developed his theory of wind-driven currents by means of the equations of fluid motion derived by Euler and Stokes. Some of the main features may be briefly summarized as follows: Assume a constant wind blowing over a large area of deep water, and neglect the effect of coasts. Because of friction each layer of water tends to move the one underneath in the direction of flow at the boundary. The resultant force on each thin layer must be zero if velocity is constant. In order that the resultant of the frictional drag above and below such a thin layer may balance the deflecting force due to the earth's rotation, the direction of the velocity in the northern hemisphere must rotate to the right as the depth increases The magnitude must also decrease Subject to these simplifying restrictions, a region sufficiently deep and so far away from coasts that their influence can be neglected, Ekman worked out the complete solution of the problem. He found the change in direction to be proportional to the change in depth and the magnitude to decrease as an exponential function of the depth At the "depth of frictional resistance," D, the direction is reversed and the magnitude is less than four per cent of that at the surface The value of D depends upon the coefficient of eddy viscosity and the latitude, and is of the order of 200 meters The surface velocity, V_o is proportional to the frictional drag of the wind and directed at 45° to the right of the wind in the northern hemisphere. The resultant flow of the whole column of water is to the right of the wind and equals 2/9 (V_o D)

A constant gradient due, for example, to a constant slope results in a constant velocity U_o at right angles to the gradient and of such a magnitude that the deflecting force balances the gradient Owing to the frictional drag of the bottom a component of velocity develops in the direction of the pressure gradient in the layer of depth D. The flow in the direction of the gradient is 0.16 (U_o D) and that perpendicular to it is 0 84 (U_o D) within this layer. These three simple type circulations can be so combined that the resultant agrees approximately with actual conditions. For example over the Pacific coastal waters of North America there is a large component of wind directed southward, and parallel to the coast, resulting in a wind current superimposed on a gradient current due to the flow of surface water seaward from the coast. This is replaced by colder water flowing from lower levels toward the coast and upwelling to the surface

To make theories of oceanic circulation as serviceable as possible Ekman suggested the following procedure which greatly reduces the difficulty of obtaining a solution corresponding to complicated boundary conditions First choose a number of simple type problems that serve as a schematic representation of the different conditions of motion in the sea Solve these relatively simple problems accurately by means of equations of fluid motion. The steady motion computed from the actual differences in density and level in the sea and the actual prevailing winds is identical with the actual one except for trivial periodic variations. In order to calculate the motion from a given density distribution, formulate an elementary type problem corresponding most nearly to it and regard the deduced motion as geometrically similar to the actual If necessary one can interpolate between two type problems Then so determine the arbitrary constants in the type problems that the calculated velocities agree approximately with the actual ones.

CALCULATION OF THE VELOCITY OF OCEAN CURRENTS FROM THEIR EFFECT ON TEMPERATURE DISTRIBUTION

In the absence of ocean currents the distribution of conservative physical and chemical properties of sea water such as temperature, salinity, and oxygen content may be denoted by the word "normal" The actual distribution of these properties may be regarded as a modification, due to ocean currents, of the normal distribution Masses of water thus moving along more or less well-defined courses tend to preserve their physical and chemical properties as they move along By attempting to deduce a circulation that would account for the departures from normal values of one of these properties, velocities of ocean currents can be calculated from their effects without regard to the forces that generate and maintain them.

For example, consider the temperature distribution as an index of circulation The quantity of radient energy that passes through a unit area of the sea and is absorbed by a thin layer of water varies directly as its thickness and is assumed to be proportional to the amount of radient energy that reaches a horizontal surface Energy leaves this layer, because of back radiation and evaporation, at a rate approximately proportional to the temperature departure from a constant corresponding to the latitude. The time rate of change of the energy in this volume equals the difference between the rate at which energy enters and leaves If the water flows horizontally and there is a temperature gradient in line with the direction of the flow, the product of this gradient by the velocity is proportional to the rate at which energy enters or leaves the volume due to the current

The average of the surface temperatures corresponding to a given circle of latitude tends to approximate to the "normal" for that latitude as the number of observations increases, if they are so distributed as to be representative An equation has been derived between the temperatures, observed and normal, at two points along a stream line, and the velocity of the current between them It has been applied to numerous temperature observations made in the North Eastern Pacific, and the estimates of horizontal current velocities agreed well, on the average, with values obtained by other methods The same principle has also been successfully used to calculate the very much smaller velocity of vertical currents, and in connection with Ekman's theory it served to explain the presence of abnormally cold water off the coast of California and to relate the amount of temperature reduction to the strength of the winds over the ocean. The vertical velocity thus estimated agreed well with that found by the Knudsen equation of the flow of water and salts in a given closed volume The flow of water out of the volume included the rate of evaporation into the atmosphere

Typical results for horizontal currents are presented in Table 1 where estimates from wind velocity are arranged in their order of magnitude and corresponding estimates from temperature are entered for comparison. In both methods a steady state of motion and temperature distribution is assumed. On the average the results of the two methods agree, but because of high variability numerous observations are required to obtain precise results.

TABLE 1

OBSERVED WINDS, ESTIMATES IN MILES PER HOUR OF OCEAN-CURRENT VELOCITIES FROM WINDS ACCORDING TO EKMAN'S THEORY, AND FROM TEMPERATURE

												Mean
Wind vel	18.9	20.0	18.0	8.8	13.0	13.0	11.0	11.0	9.5	7.0	7.0	12.5
Current from wind	0.62	0.49	0.33	0.27	0.23	0.22	0.20	0.19	0.17	0.15	0.14	0.27
Current from temp	0.10	0.72	0.09	0.07	0.20	0.34	0.15	0.65	0.10	0.28	0.13	0.26

SUPPLEMENTARY CONSIDERATIONS AND CONCLUSIONS

The instantaneous or synoptical motion in the sea is conveniently represented by *stream-lines* or curves such that the tangent at every point has the direction of the velocity there. Such a representation is called a current field. In general, the inclination of stream-lines to the sea surface is very small and they must satisfy certain conditions: (1) Different stream-lines cannot intersect. (2) They neither begin nor end in the current field except in certain *singular points* and lines.

Stream-lines are continuous curves throughout most of their length, but certain limited parts may have discontinuities. A line towards which two systems of stream-lines converge is called a *line of convergence* (arrows point toward the line) A line from which two systems of stream-lines diverge (arrows point away from the line) is called a *line of divergence.* Again, stream-lines may converge to a point or diverge from a point, or one system of lines may converge to a point and another system may diverge from the same point In general a line or point of convergence implies a downward flow while a line or point of divergence implies an upward flow in order that the condition of continuity may be satisfied Such vertical velocities may also result from changes in velocity along parallel stream-lines

Not only the configuration of the coast lines but also the bottom topography exerts an important influence on oceanic circulation Neglect at first the effect of compressibility, friction and the deflecting force due to the earth's rotation, and assume that the motion does not vary with time, as denoted by the phrase, "stationary condition." Water adjacent to the bottom of the coast must move along these boundaries. That is, the stream-lines at the boundaries must run parallel to the boundaries Accordingly, the effect of the accompanying lateral departures of currents from rectilinear courses may extend for a considerable distance from the coast and from the sea bottom For example, if the bottom departs from a plane in an undulating or wave-like manner the stream-lines of a current flowing across the crests and hollows will have a similar wave-like departure from horizontal lines. The phase and magnitude of these departures depend upon the velocity of the current, depth of the water, and horizontal distance between the crests A similar distortion of isotherms and isohalines may result, and vertical departures even exceeding 100 meters have been observed When a layer of light water rests on one of relatively heavy water such disturbances may have little or no effect on the surface although at the boundary they may be greatly amplified In general the circulation in the sea tends to undulate about simpler average courses.

In his earlier investigations on wind-driven currents Ekman assumed the depth to be uniform, but estimated the influence of the bottom when the depth is less than the "depth of frictional influence," *D*. Later he investigated the more difficult problems of determining the effect of a variable depth on circulation. He found that a uniform increase in depth in a direction parallel to the coast caused a decrease in velocity of the mid-water current as the distance perpendicular to the coast increased, assuming the wind to be parallel to the coast and in the direction of the increasing depth If the depth varies in an undulating manner, Ekman concluded that the deep-water current would undulate in a horizontal direction, and that the effect is due to the absolute variation of the depth rather than to a variation relative to *D*. The following general principles formulated by Ekman summarize the results Where the depth increases in the direction of a current a vortex *contra solem* tends to form; where the depth decreases in the direction of a current a vortex *cum sole* tends to form, and where the current follows the direction of bottom contours no disturbance of the current-field results from the bottom topography.

In general, any conditions causing a local accumulation of water in one part of the sea and removal of water from another part will alter the sea surface and thus cause gradient-currents. This alteration will continue until the rates of inflow and outflow balance throughout, assuming winds and other external influences to be stationary Ekman deduced the general law that a depression of the sea surface causes a rotational motion *contra solem*, and an elevation, a rotational motion *cum sole*

The practical value of Ekman's theory of stationary wind-driven ocean currents depends partly upon the length of time required for the wind to generate a current velocity approximating its limiting value. His investigation of this difficult problem resulted in the following conclusions, assuming the depth to exceed *D*, and excluding a belt close to the equator: the time required for a wind-driven current to attain any proportion of its limiting value is independent of the coefficient of friction The stationary state will be nearly established in a few days' time within about 100 kilometers from the coast and for moderate depths, less than 500 meters (*i e* , on the continental shelves). The time increases with the depth of the sea, the breadth of the current, and the latitude, and may amount to several weeks The surface current is practically established in a few hours' time and responds quickly to changes in the wind Later estimates by Jeffreys and Proudman agree as to the order of magnitude of the time required for a current to approximate to its stationary value Accordingly we should, in general, expect a circulation approaching the stationary state to exist and the corresponding theory to apply approximately to actual conditions.

There is, in general, a continual increase of density *in situ* from the surface downward Any small volume of water lighter than the average at that level tends to rise, if heavier, it tends to sink. Thus the extreme mobility of water results in a stratification according to the density and therefore according to temperature and salinity Moreover, such stratification from the lightest water at the surface down to the heaviest water at the bottom corresponds to a condition of stable equilibrium in which the center of gravity is as low as possible. A body of water thus stratified resists any force (*i.e.*, frictional drag of the wind) tending to change the relative positions of the different strata If distorted it tends to return to its equilibrium condition This resistance to change may be indicated numerically by the amount of work that must be expended in order to transform the stratified body of water into one of equal density throughout.

Earlier investigations of the phenomena of turbulence proceeded on the assumption of an analogy between the behavior of molecules and of eddies Accordingly, the familiar classical equations of motion, diffusion, and conduction were used, in which the coefficients of viscosity, diffusion and eddy conductivity that apply to the laboratory experiments were replaced by new virtual coefficients regarded as constant in each problem. Since the virtual coefficients depend upon the character of the *turbulent motion* rather than on the properties of the substance, water or air, we have reason to believe that they would all have the same values at the same time and place According to the results of meteorological investigations, nearly the same value of the coefficient has been found for the diffusion of moisture as for the conduction of heat. Less extensive investigations of the ocean have resulted in the same coefficient for the diffusion of salinity as for the conduction of heat. While investigations of the velocity have yielded values of the virtual coefficient of viscosity of the same order of magnitude as those of diffusion and conductivity, significant differences are found Apparently, the kinetic energy is not carried unchanged by fluid masses as they move across the boundary between two layers But the same masses appear to carry other properties, temperature, salinity, etc, with but a small change. Although such a procedure adds but little to our understanding of the mechanism of turbulence, in detail, it may lead to equations agreeing very closely with observations Thus, results may be obtained of fundamental importance in the solution of other problems. Although under certain conditions only very rough approximations result, the agreement between theory and observations may be greatly improved by assuming the coefficient to vary in accordance with the stability, as has been shown by Fjeldstad and others

Believing that a much more fundamental analysis of turbulence can be worked out which would show more clearly the structure of turbulent motion, several investigators have made encouraging progress specially within the past fifteen years. In these studies detailed measurements of air motion made in laboratories designed to aid in the solution of problems of aviation, as well as atmospheric observations have contributed essential information. Important parallel advances in the theory of turbulence have been made by G I. Taylor, O G Sutton, L. Prandtl, Th. von Kármán, J M Burgers, C. G. Rossby, and others. Owing to the inherent complexity and irregularity of turbulent motion these investigators have necessarily resorted to probability methods. In particular, H Gebelein, a student of Prandtl, deduced hydrodynamical equations of motion by means of a "probability calculus" as developed in recent years by physicists to solve their problems of "statistical ensembles " The presentation of his results in a volume entitled "Turbulenz' marks a new epoch in this field and shows a distinct advance over preceding theoretical methods The oceanographer is now furnished with a developing body of information and methods that should impel him to give more attention to the theory of turbulence in the sea, and to make field observations designed to contribute to a better understanding of this important phenomenon.

In conclusion, this survey of the field of dynamical oceanography has shown that there are various indirect methods available for interpreting field observations of winds, temperature, and salinity, and that by means of these methods we can obtain a knowledge of oceanic circulation. It is only by a proper coordination of such methods with suitable direct measurements that so complex a phenomenon as oceanic circulation can be adequately investigated.

LAND MOLLUSKS FROM THE ISLAND OF ROATAN, HONDURAS

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(Communicated by Edwin G Conklin)

ABSTRACT

Mollusks were collected from Roatan, the largest of the Bay Islands, located about 40 miles off the north coast of the Republic of Honduras Sixteen species of land shells are here recorded of which four are described as new The best collecting was among the Pleistocene limestone near the western end of the island Mollusks previously collected from other of the Bay Islands are reviewed The relationship is definitely Central American Those species that do show a more or less distant relationship to the West Indies might have reached the Islands and the Central American Mainland by a Tertiary land bridge connecting Jamaica and Haiti with Nicaragua and Honduras

OUR knowledge of the land mollusks of the Bay Islands of Honduras has been limited to a paper by Ancey (1886) on a collection from Utilla and a few records from Bonacca listed by Von Martens (1890–1901) Nothing has been known of the mollusks of Roatan, the largest of the Bay Islands, and it therefore seemed desirable to make a collection from this island

ACKNOWLEDGMENTS

With the aid of a grant from the Penrose Fund of the American Philosophical Society I was able to spend a few days on Roatan in August, 1937, making a study of its molluscan fauna It is a great pleasure to express my thanks to the Society for the aid which made this work possible Allen L. Midyette was the field assistant on the trip and has also prepared the sketch map accompanying this report (Fig 1). We are indebted to the officials of the Standard Fruit Company, in particular Mr Luigi Bacuzzi of Roatan, for innumerable courtesies during the course of the work.

The study of the material was carried on at the Academy of Natural Sciences in Philadelphia and I am deeply indebted to Dr. Henry A Pilsbry of that Museum for considerable help in the preparation of this paper. I also wish to express appreciation to Dr H B Baker of the University of Pennsylvania for assistance, particularly in the matter of bibliographic references

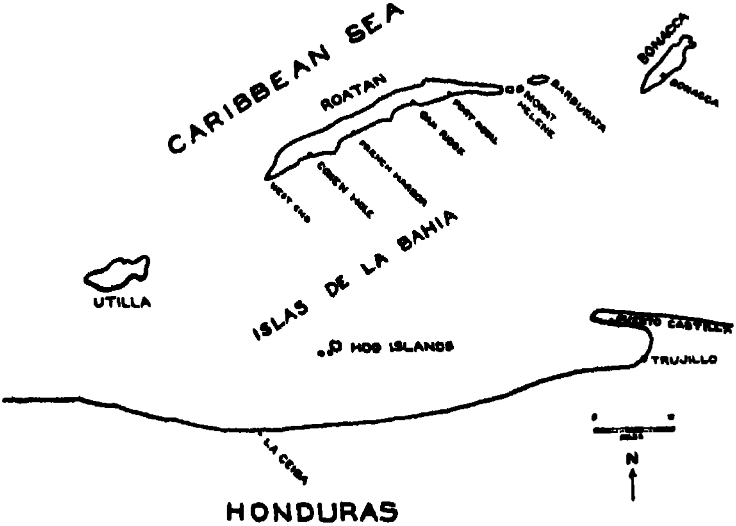

FIG 1 Sketch map of the Bay Islands of Honduras

The original set of the material, including types, is deposited at the Academy of Natural Sciences, while a duplicate set is at the Museum of Comparative Zoology in Cambridge, Massachusetts

LOCATION

The Bay Islands (Islas de la Bahia) consist of a small group of islands in the Caribbean Sea from 10 to 40 miles north of the Republic of Honduras Roatan, the largest of the group being about 30 miles long and 9 miles wide, lies about 30 miles from the mainland

Roatan is fairly accessible by small schooner from La Ceiba on the mainland and it was from this port that we sailed on

August 11, 1937. Coxen Hole, the largest town on Roatan and the capital of the Bay Islands (Pl I, Fig 2), was our headquarters. Our collecting trips were made in different directions from Coxen Hole, and while it was impossible to cover the entire island, we were able to visit representative localities Upon the completion of the collecting we obtained passage on a small schooner (*El Pato*) for Belize, British Honduras, 180 miles distant, from which port another schooner (*Delphia*) took us to Tampa, Florida

TOPOGRAPHY AND GEOLOGY

Roatan has a mountainous west to east backbone and reaches a height of about 800 feet near the western end There are no rivers on the island, merely small streams many of which terminate in dense mangrove swamps For a brief description of the island together with a detailed account of the archeology see Strong (1935)

The Bay Islands are a seaward extension of the Sierra de Omoa of northwestern Honduras, and consist of ancient crystalline rocks of Paleozoic or Pre-Cambrian age (Schuchert, 1935, pp 351, 357, 371). The west end of Roatan consists of Pleistocene coral limestone up to 10 feet above the sea (See Pl. II)[1]

ECOLOGICAL NOTES

The dense jungle of the interior of the island (Pl I, Fig 1) was not very rich in mollusks However, careful search among the humus yielded a number of species of which *Poteria dysoni*, *Subulina octona*, *Lucidella midyetti* and *Alcadia dysoni jansoni* were the most common Our best stations for shell collecting were among the limestone outcrops near West End (Pl II). Here the shells were frequently abundant in the crevices of the rock *Brachypodella bourguignatiana*, *Microceramus concisus arctispirus*, *Choanopoma andrewsæ roatanensis* and *Streptostyla coxeni* were the most characteristic species of this association. _Truncatella bilabiata_ was also present on this limestone, especially near the shore.

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[1] For further notes on the geology of Roatan see Sapper (1905), Powers (1918), Redfield (1923) and Sapper (1937, p 108, Pls 1, 7)

PREVIOUS LITERATURE ON CENTRAL AMERICAN MOLLUSCA

The classic works on the terrestrial mollusks of Central America are those of Fisher and Crosse (1870–1900) and Von Martens (1890–1901). The fauna of Yucatan has been treated by Pilsbry (1891) and more recently by Bequaert and Clench (1933, 1936). A recent paper by the present writer (Richards, 1937) discussed the fauna of Cozumel Island.

The mollusks of Guatemala have been discussed recently by Hinkley (1920) and by Goodrich and Van der Schalie (1937).

The paper by Ancey (1886) mentioned above records 19 species collected by C. T. Simpson from Utilla in the Bay Islands of Honduras. His list is given below. When changes in nomenclature have taken place, the original name is given in parenthesis. The specimens marked with an asterisk (*) have been examined in the Academy of Natural Sciences of Philadelphia.

Euglandina carminensis (Morelet)
(_Glandina carminensis_ Morelet)
Streptostyla thomsoni Ancey
Salasiella perpusilla (Pfeiffer)
(_Oleacina perpusilla_ Pfeiffer)
Guppya utillensis (Ancey)
(_Conulus utillensis_ Ancey)
Thysanophora cæcoides (Tate)
(_Pseudohyalina cæcoides_ Tate)
Thysanophora hornii (Gabb)
(_Helix horni_ Gabb) [1]
*_Microceramus concisus arctispirus_ (Ancey)
(_Macroceramus gossei arctispirus_ Ancey)
*_Brachypodella bourguignatiana_ (Ancey)
(_Cylindrella bourguignatiana_ Ancey)

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[1] Probably a misidentification since _T. hornii_ Gabb is restricted to Arizona and northern Mexico.

**Lamellaxis simpsoni* (Ancey)
(*Nothus simpsoni* Ancey)
**Lamellaxis mexicanus utilensis* Pilsbry
(*Nothus mexicanus* Pfeiffer)
**Lamellaxis fordianus* (Ancey)
(*Nothus fordianus* Ancey)
Lamellaxis gracilus (Hutton)
(*Opeas subulata* Pfeiffer)
Poleria dysoni (Pfeiffer)
(*Aperostoma dysoni* Pfeiffer)
**Choanopoma andrewsæ* (Ancey)
(*Cyclostoma andrewsæ* Ancey)
Helicina amœna Pfeiffer
Helicina tenuis Pfeiffer
(*H lindeni* Pfeiffer)
Alcadia dysoni (Pfeiffer)
(*Helicina dysoni* Pfeiffer)
Pyrgodomus simpsoni (Ancey)
(*Trochetella simpsoni* Ancey)
**Lucidella lirata* (Pfeiffer)
(*Helicina unidentata* Pfeiffer)

Von Martens (1890–1901, pp 29, 40) mentions the following two species collected by Gaumer from Bonacca

Alcadia dysoni jansoni (Von Martens)
(*Helicina dysoni jansoni* Von Martens)
Helicina oxyrhyncha Crosse & Debeaux[1]
(*H rynchostoma* Shuttleworth)

The fauna of the Swan Islands, which lie in the Caribbean Sea about 160 miles northeast of Roatan and 100 miles north of Laguna Caratasca, Honduras, has been studied by Pilsbry (1931). In this same paper is treated the fauna of other smaller Caribbean islands including Old Providence, St Andrews, and the Cayman Islands.

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[1] Ancey (1904) notes that the specimens in the British Museum from Bonacca labelled *H oxyrhyncha* are not identical with the type specimens of Crosse and Debeaux (1863) the locality of which is unknown Pilsbry (1927) records *H oxyrhyncha* C & D from Panama Von Martens records *H. rynchostoma* Shuttleworth (= *H oxyrhyncha* C & D) from Colombia and Venezuela

LAND MOLLUSKS FROM ROATAN

Oleacinidæ

Euglandina cumingi Beck

Between Coxen Hole and North Side, between Coxen Hole and French Harbor, West End

Known from Central America from Yucatan to Panama, also from Venezuela

Streptostyla coxeni new species (Pl III, Fig. 2)

The shell is cylindric-oblong with conic spire and relatively acute apex, somewhat glossy Color unknown as the two specimens are bleached to an extremely pale brown tint 5½ whorls, the first 2½ smooth, the remaining with sculpture of subregularly spaced axial grooves Columellar fold moderately strong as in *S meridina* Morelet.

Length 6 25 mm , diameter 2 3 mm ; length of aperture 3 3 mm The type (A.N S P 170020) and one other shell were collected on the limestone outcrops between Coxen Hole and West End

The species resembles *S meridina* Morelet of Yucatan and Central America in shape but is smaller and is easily recognized by its conspicuous grooves.

Zonitidæ

Guppya gundlachi (Pfeiffer)

Between Coxen Hole and French Harbor

Of widespread distribution in Mexico, Central America and the West Indies

Fruticolidæ

Averellia (Trichodiscina) coactiliata (Deshayes)

Between Coxen Hole and French Harbor; North Side, West End

A very common Central American form known from Vera Cruz to Panama

Urocoptidæ

Brachypodella bourguignatiana (Ancey)

West End (rare)

Hitherto known only from the type locality on Utilla.

Microceramus concisus arctispirus (Ancey)

West End

This variety has been previously reported only from the Island of Utilla *M concisus* (Morelet), which differs very slightly from the variety, is reported from Yucatan, Cozumel, Guatemala, Swan and St. Andrews Islands.

Subulinidæ

Subulina octona Bruguiere

Common at all stations especially between Coxen Hole and North Side.

Widespread throughout all the tropics

Lamellaxis micra (d'Orbigny)

(*Opeas micra* (d'Orbigny))

Between Coxen Hole and French Harbor, West End

Of wide distribution throughout tropical America

Lamellaxis mexicanus (Pfeiffer)

(*Leptinaria mexicana* (Pfeiffer))

Between Coxen Hole and French Harbor, West End.

Known from Mexico, Guatemala and Nicaragua The Roatan specimens are not *L mexicanus utilensis* Pilsbry of Utilla Island.

Succineidæ

Succinea recisa Morelet

Between Coxen Hole and French Harbor, West End.

Reported from the mainland of Guatemala, Nicaragua and Costa Rica

Cyclophoridæ

Poteria dysoni (Pfeiffer)

Between Coxen Hole and North Side.

Reported from the mainland from the State of Vera Cruz to Panama. Ancey found the species on Utilla

Pomatiasidæ

Choanopoma andrewsæ roatanensis new variety

(Pl III, Figs. 1, 7)

Resembles the typical *andrewsæ* Ancey except that the ribs are somewhat thinner and the shell is slightly more tapering In some individuals a spiral series of sparse chestnut-brown dots are developed on the lower three whorls In this respect the shell resembles *C cozumelensis* Richards, but is distinguished by its thinner ribs and more slender shape.

Type (A N S P 170018). Length 10 25 mm ; width 6 0 mm , width of aperture 4 0 mm.

West End, fairly common in crevices in limestone

C andrewsæ Ancey is known only from the Island of Utilla The other related species, *C. cozumelensis* Richards, was described from the Island of Cozumel

Helicinidæ

Alcadia dysoni jansoni (Von Martens) (Pl. III, Figs. 5, 6)

Common at all stations

This variety was described from the Island of Bonacca and has not been recorded elsewhere *A dysoni* (Pfeiffer) was reported by Ancey on Utilla

Helicina hondurana new species (Pl III, Figs 8, 9)

The shell is depressed, subacutely carinate in the middle, the outlines of the conic spire slightly convex, base weakly convex Upper surface after the whitish apex is sulphur yellow changing in the last whorl to pale pinkish buff, with two banks of irregular pinkish cinnamon spots near the suture and near the periphery The base is sulphur yellow, the callus mustard yellow Aperture subtriangular, the interior yellow brown and pinkish cinnamon above. The lip is nearly white, reflected, produced in a short blunt mucro or projection at the position of the keel. The parietal callus spreads rather far forward, where the edge is indistinct. There is a small tooth at the base of the columella.

Height 8.7 mm , diameter 12 7 mm ; 5½ whorls.

The type (A.N.S P 170019) from West End; also collected from between Coxen Hole and North Side and between Coxen Hole and French Harbor.

The species resembles *H rostrata* Morelet (from Guatemala) in general appearance but differs from it in being more carinate, more depressed and by having a much blunter projection on the outer lip. *H denticulata* Pfeiffer, known from San Pedro and Lancetilla, Honduras, is probably also related, but is even more conic. *H oxyrhyncha* Crosse and Debeaux (from Panama, Colombia, Venezuela and Bonacca (?)) is another mucronate form but can be distinguished by its more prominent sculpture and by the absence of the columellar tooth.

Lucidella midyetti new species (Pl III, Figs 3, 4)

The shell is cinnamon rufous, about equally convex above and below, acutely carinate, the keel bearing a rather wide periostracal border which is largely or wholly lost in the adult stage, but often fragments persist especially in the penult whorl where it overlaps the suture of the last whorl. After the smooth embryonic shell it has spiral threads as in *L. lirata* (Pfeiffer), usually about half as wide as their flat intervals, which show minute retractive growth striæ There are generally about seven above the keel and an equal number or more below the base. The central region of the base is without spiral threads The aperture is shaped much as in *L lirata* The outer margin of the peristome is thin and expanded, the basal margin slightly reflected and a little thickened showing only a very slight thickening or none at the position of the tooth of *L. lirata.* The thin parietal callus is strewn with granules, more conspicuous than in *L lirata*

The species is closely related to *L. lirata* but differs conspicuously as follows: It is larger and distinctly more depressed, more prominently carinate, the whorls are flatter, the lip is thinner and reflected less than in *L lirata* The presence of the laminæ is also characteristic of this species

Type (A N S.P. 170021). Diameter 5.4 mm., height 3.2 mm.

Cotype. Diameter 3 2 mm , height 2 8 mm.

Type locality between Coxen Hole and French Harbor; also collected from between Coxen Hole and North Side and from West End. Common.

Named in honor of my assistant Allen L. Midyette.

L lirata (Pfeiffer) is a common species of the West Indies, Central America and northern South America (Venezuela). Ancey recorded it (as *Helicina unidentata* Pfeiffer) on Utilla.

Truncatellidæ

Truncatella bilabiata Pfeiffer

West End, living on Pleistocene limestone along the shore.

This species is characteristic of mangrove swamps and brackish water associations Shells are known from Florida, Cuba, the Bahamas, West Indies, Yucatan, Swan and Old Providence Islands With the exception of the shells from Yucatan, no specimens are reported from the mainland of Central America

ZOOGEOGRAPHY

The mollusca of the Bay Islands may be grouped as follows

Restricted to the Bay Islands

Streptostyla thomsoni Ancey U
Streptostyla coxeni Richards R
Guppya utillensis Ancey U
Brachypodella bourguignatiana Ancey U R
Microceramus concisus arctispirus Ancey U R
Lamellaxis simpsoni Ancey U
Lamellaxis fordianus Ancey U
Lamellaxis mexicanus utilensis Pilsbry U
Choanopoma andrewsæ Ancey U
Choanopoma andrewsæ roatanensis Richards R
Alcadia dysoni jansoni Von Martens B R
Pyrgodomus simpsoni Ancey U
Helicina hondurana Richards R
Lucidella midyetti Richards R

Primarily of Central American Relationship

Euglandina carminensis Morelet U
Euglandina cumingi Beck R
Salasiella perpusilla Pfeiffer U
Thysanophora cæcoides Tate U

Thysanophora hornii Gabb (?) U
Averellia coactiliata Deshayes R
Lamellaxis mexicanus Pfeiffer R
Succinea recisa Morelet R
Poteria dysoni Pfeiffer U R
Alcadia dysoni Pfeiffer U
Helicina tenuis Pfeiffer U
Helicina amœna Pfeiffer U
Helicina oxyrhyncha Crosse and Debeaux (?) B

Primarily of West Indian Relationship

Lucidella lirata Pfeiffer U
Truncatella bilabiata Pfeiffer R

Of General Tropical American Distribution

Guppya gundlachi Pfeiffer R
Subulina octona Bruguiere R
Lamellaxis micra d'Orbigny R
Lamellaxis gracilus Hutton U

U = Utilla. B = Bonacca R = Roatan

The relationship is definitely Central American With the exception of *Lucidella midyetti* all the endemic species of the Bay Islands are more closely related to mainland forms than to those of the West Indies The West Indian *Truncatella bilabiata* is of widespread distribution and could easily have been transported by human agency The genus *Lucidella,* although known from Central America, is more characteristic of the West Indies (Jamaica) Those forms that do show a more or less distant relationship to the West Indies (*Brachypodella, Choanopoma, Lucidella*) might have reached the Islands and the Central American mainland by the Tertiary land bridge connecting Jamaica and Haiti with Honduras and Nicaragua, as discussed by Schuchert (1935, pp 107-8). This origin of certain elements of the Central American fauna from the West Indies agrees with views expressed by the writer (Richards, 1937) in discussing the fauna of Cozumel.

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FIG. 1. Jungle Trail, Roatan.

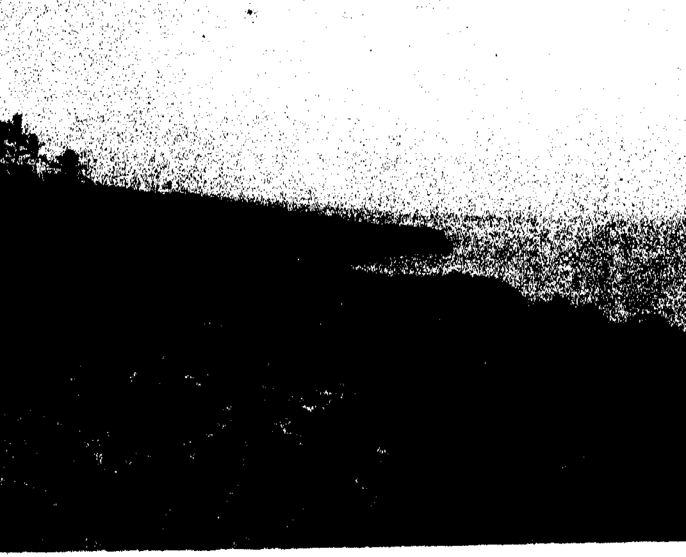
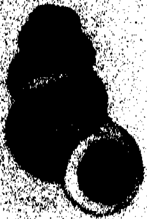


FIG. 1. Limestone near West End, Roatan.



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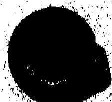

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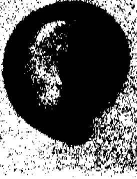

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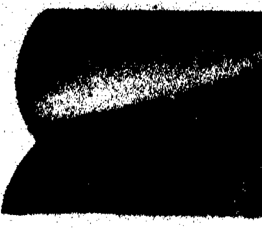

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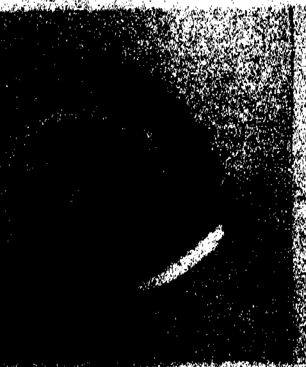

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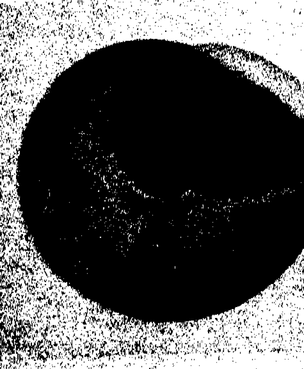

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1. *Choanopoma andrewsæ roatanensis* Richards. Fig. 2. *St*
Richards. Fig. 3. *Lucidella midyetti* Richards. Fig. 4.

DISORIENTATIONS OF DEVELOPMENT IN CREPIDULA PLANA PRODUCED BY LOW TEMPERATURES

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(*Read April 21, 1938*)

ABSTRACT

The orientations of the developing egg are caused by vortical movements (plasma flowing) which bring about segregation of structures and substances in the chief axis of the egg and later in the cells into which the egg divides In *normal development these vortical currents run in preëstablished directions* and lead to the typical localization of substances and cells in development

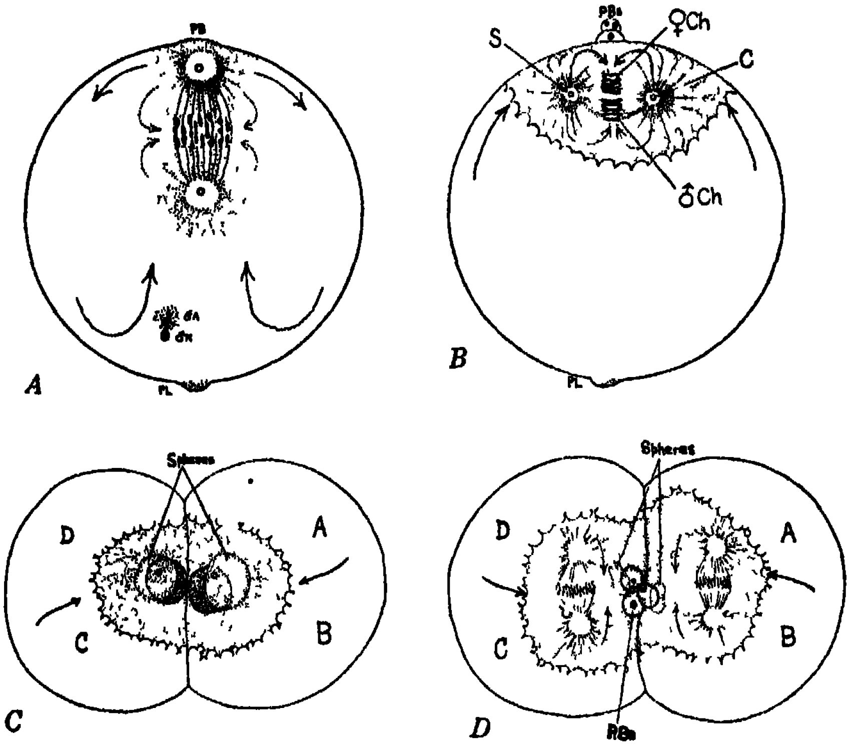
If the developing eggs of the marine gasteropod, Crepidula, are kept at a temperature near freezing for a few hours, plasma flowing and cell divisions are stopped though dividing nuclei may finish division and resting nuclei may grow and prepare to divide After such eggs are returned to temperatures of about 20°C, plasma flowing is resumed but often in abnormal directions with the result that the directions of division walls and the positions and contents of the cells are abnormal Sometimes the plasma flowing is resumed at a later stage than that at which it was stopped, with the result that certain early cell divisions are entirely omitted whereas later divisions are normal, except for the reduced number of cells In short all developmental processes are not stopped at the same time by cold and even though *certain stages of development* are omitted altogether the development may go forward from a later stage, as if the factors of development were active during refrigeration although the typical expression of those factors is suppressed

NEARLY forty years ago I called attention to the importance of "Protoplasmic Movement as a Factor in Differentiation" (Conklin, 1899) and three years later I dealt with this subject in a monograph on "Karyokinesis and Cytokinesis" (Conklin, 1902) In both of these papers I showed that definite vortical movements during mitosis in the egg and cleavage cells of Crepidula bring about the typical orientations of mitotic figures and cleavage planes and the differential localizations of different oöplasmic substances. Such vortical movements had been observed by v Erlanger (1897) and Bütschli (1900) in the eggs of nematodes, but the importance of these movements in the localization of the substances of the egg and in embryonic differentiation had not been determined previously Since then such movements have frequently been observed in the eggs of different species of animals, and especially in annelids, mollusks and ascidians

I TYPICAL MOVEMENTS IN MATURATION AND FERTILIZATION

The earliest intracellular movements which I have observed are those which accompany the maturation and fertilization of the egg In all animals the nucleus of the egg before maturation is relatively large and a large amount of the nuclear contents is set free into the cell body when the nuclear membrane breaks down in the first maturation mitosis In annelids, mollusks, ascidians and probably in other phyla also vortical movements within the cytoplasm occur coincidently with the escape of this nuclear material I have studied these movements more particularly in gasteropods and ascidians and in these forms there is movement up through the egg axis to the animal pole and down over the surface toward the vegetative pole (Fig *A*) The maturation spindle when first formed lies some distance from the animal pole and its axis may lie at any angle with the egg axis, but by means of this vortical movement the hyaloplasm and nuclear contents go up to the animal pole and are there spread out over the surface while the spindle is usually turned into the egg axis and its upper end comes into contact with the surface at the animal pole. If the egg is not fertilized these movements stop permanently at this point, but if a spermatozoon has entered, the movements go on until the maturation spindle is thrust up against the egg membrane at the animal pole and the surface layer is pushed out at this point (Fig *A*). At the same time the spindle grows shorter and wider as if due to this pressure and finally the first polar body is cut off, the division wall passes through the middle of this shortened spindle, thus giving rise to a very small cell, the first polar body. In similar manner the second maturation spindle is oriented and the second polar body given off under the first.

While the movements accompanying the formation of the first and second polar bodies are taking place, the sperma-



TEXT FIG 1 Typical eggs of *Crepidula plana* showing by arrows the direction of plasma flowings *A* and *B* viewed from one side, animal pole at top, *C* and *D* viewed from the animal pole *A*, first maturation mitosis the flow being up through the center and down over the surface, the mitotic vortices are indicated by small arrows *B*, first cleavage mitosis, the plasma flowing up over the surface and down in the cleavage plane *C*, telophase of first cleavage, showing final stage of first cleavage vortex, which was slightly dexiotropic in each cell *D*, metaphase of second cleavage showing plasma vortex slightly læotropic—*PB*, polar body, *PL*, polar lobe, *C*, centrosome, *S*, sphere, ♂*A*, sperm aster, ♂*N*, sperm nucleus, ♂*Ch*, sperm chromosomes, etc *A*, *B*, *C*, *D*, positions of future macromeres

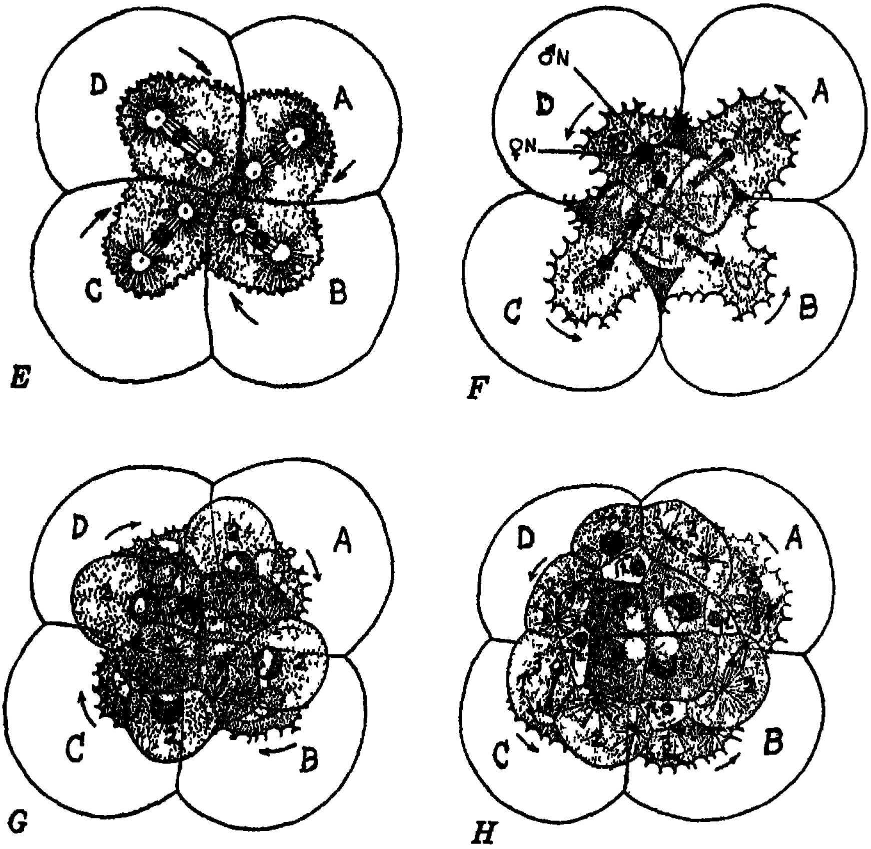
tozoön, which has entered the egg generally in the lower hemisphere, moves into and up through the egg axis, the sperm nucleus being preceded by the sperm aster (Fig. *A*) In gasteropods this movement continues until the sperm aster and nucleus come into contact with the egg aster and nucleus in the area of clear cytoplasm at the animal pole At the same time the layer of cytoplasm at the animal pole flows down over the surface toward the vegetative pole, while there is an upward flow through the interior of the egg toward the animal pole. This is plainly a vortical movement, comparable to the movement of particles in a smoke ring

In ascidians and amphioxus in which there is no egg aster the egg nucleus moves down from the animal pole toward the ascending sperm aster and nucleus until the two nuclei meet near the equator of the egg and on one side of the center, which later development shows to be posterior. It is evident that other factors than the original maturation vortex are involved here No doubt the sperm aster is a factor, since asters in general are centers of cytoplasmic flowing But the orientation of these movements accompanying maturation and fertilization is determined primarily by the polarity of the egg, and in ascidians and amphioxus by its bilateral symmetry also.

In Crepidula a path of hyaloplasm is frequently seen at this stage running in the egg axis from the vegetative to the animal pole, and at the vegetative pole there is an accumulation of hyaloplasm which protrudes as a small "polar lobe" at each maturation division, as well as at the first and second cleavages (Figs *A*, *B*) The animal and vegetative poles are thus clearly marked by the polar bodies and the polar lobe Protrusion of the surface opposite the poles of the amphiaster is a common phenomenon throughout the cleavage and I have shown elsewhere (1912) that the tension of the surface layer is reduced at these points.

II TYPICAL MOVEMENTS DURING CLEAVAGE

Vortical movements, which are in reverse directions at the two poles of the amphiaster, are very evident during the early cleavages of the egg of Crepidula. I have described these in previous publications (1897, 1902) and in this place I call attention merely to the fact that the location and direction of



Text Fig. II. Typical cleavages of *Crepidula plana*, showing directions of vortices in each cell. *E*. Prophase of third cleavage, the plasma flow being in an apical-dexiotropic direction. *F*. Late anaphase of third cleavage, showing the plasma flow in a dexiotropic direction in the micromeres (1) and læotropic in the macromeres (*A*, *B*, *C*, *D*). *G*. Twelve-cell stage, the macromeres have given off the second set of micromeres (2) in a læotropic direction and the plasma flow in these micromeres is also læotropic, while it is dexiotropic in the macromeres. The first set of micromeres is dividing in a læotropic direction. *H*. Twenty-cell stage, the first set of micromeres has divided læotropically into the central cells (1^1), in which the plasma flow is læotropic, and the turret cells (1^2), in which the flow is dexiotropic. The second set of micromeres (2) are dividing læotropically and the macromeres have just given off the third set (3) in which the flow is dexiotropic, while it is læotropic in the macromeres.

mitotic figures and cleavage planes are determined by these vortical movements of the cell contents; also the segregation and isolation of different substances in the different cleavage cells is brought about by these same movements. The directions of these vortical movements during the early cleavages of Crepidula are indicated in the accompanying figures *C–H*, in which it will be seen that at each cleavage the vortices at the poles of the amphiaster are greater on the animal pole side of the cell than on the opposite side, and that there is a spiral twist of the vortices of each cleavage, that of the first being clockwise (Fig *C*), the second counter-clockwise (Fig *D*), the third clockwise (Fig *E*), etc

In typical cleavage of Crepidula the first four blastomeres are approximately equal, from these, three quartets of micromeres are separated which subdivide and give rise to the entire ectoderm (Figs *G*, *H*, 1, 2, 3), a fourth micromere (mesomere, 4*d*) is formed from the left posterior macromere *D* and gives rise to practically all the mesoderm, while the remaining portions of the macromeres constitute all of the endoderm. Thus at the 25-cell stage the three germinal layers are segregated in 20 ectoderm, 1 mesoderm and 4 endoderm cells. It is important to recall these well-known facts of the normal cleavage and differentiation in Crepidula, in order to appreciate the changes induced by experiments

III Experimental Modifications of Mitotic Movements

Intra-cellular movements accompanying maturation, fertilization and cleavage of the egg may be altered or stopped in many ways,—by pressure, centrifugal force, lack of oxygen, anæsthetics, hypertonic solutions, cold, etc.,—but the actual causes of these movements, like the real causes of amœboid, ciliary or muscular contractility, are largely unknown. These vortical movements are usually very slow and can be seen only indirectly by comparing successive stages in development, although in nematodes and ascidians they are sometimes rapid enough to be seen directly in living eggs.

The present paper deals with the effects of cold on these ooplasmic movements during maturation, fertilization and cleavage in the eggs of *Crepidula plana*. Attention was first called to these effects by the remarkable disorientations of mitotic figures and cleavage planes in eggs which had been kept over night in a refrigerator in order temporarily to stop development Following this, a long series of experiments was undertaken to determine (1) the most effective temperatures and stages for causing these disorientations, (2) the manner in which they are produced, and (3) the effect of such disorientations on later development

1 *The most effective temperature* was found to lie between − 1° and + 5° C for a period of from 2 to 20 hours or more, some eggs indeed were kept at a temperature of 5° C for 3 days without destroying their ability to divide when returned to water of about 20°. All mitotic figures and division planes from the first maturation division to the 8-cell stage, or even later, may be disorientated by cold, intermitotic stages and late cleavages are affected relatively little. This is significant as indicating that it is the movement accompanying mitosis and cell-division that is chiefly affected by cold

2 *Modifications of Cytoplasm and Nuclei While Still in Cold.*—The most evident direct effect of cold treatment is to cause the hyaloplasm throughout the egg to clot or contract into islands, which are often connected by strands. A principal strand, which is usually present before the first cleavage, runs from the animal to the vegetative pole along the egg axis (Figs 2, 3, 5, 9) Other strands or lines of islands may be roughly radial around the asters or centrospheres (Figs. 2, 6, 46, 48). Associated with this clotting there is evidently a loss of water from the cell since the cell membrane is usually wrinkled or irregular when the clots are most evident (Figs. 2, 6, 47). On return to room temperature the eggs regain their smooth outlines and the clots disappear in a short time (½ to 2 hours).

Eggs with nuclei in the resting stage that have been kept for 8 or more hours near 0° C. have enormously large nuclei and nucleoli, thus showing that resting nuclei may continue to absorb fluid from the cell body at these low temperatures (Figs. 48–51, 64). Centrospheres also may be very large in such eggs (Fig 6 sp , 48, 56, 64) but it is often difficult to distinguish centrospheres from cytoplasmic islands or clots (*e g.* Figs 46, 47, 56) Chromosomes may form rings, masses or equatorial plates within such enlarged nuclei (Figs 50, 51, 56) or if the nuclear membrane has dissolved in the prophase the nuclear contents may elongate in the form of an abnormal mitotic figure (Figs 52–55) which is frequently disoriented.

3 *Effects of Gravity on Eggs Subjected to Cold.*—Crepidula eggs do not orient with respect to gravity and under normal conditions cytoplasm collects at the animal pole and yolk at the vegetative irrespective of the relation of the egg axis to the direction of gravity But when eggs are left undisturbed in the refrigerator for long periods during which the normal vortical movements are stopped the lighter cytoplasm and heavier yolk may be partially separated in the direction of gravity, as in Figs 1, 6, 9, 10, 14, 62, 63, 87 This separation is similar in effect to that caused by weak centrifugal force. Refrigerator eggs in the 2-cell stage often have their cytoplasm carried down into the cleavage furrow toward the vegetative pole (Figs 46, 52–55), probably owing to the long-continued action of gravity on eggs with the vegetative pole up. Sometimes cytoplasm and nucleus are lodged against the first cleavage furrow in one cell and carried away from it in the other (Figs 53, 54), this is the condition found in eggs which have been centrifuged in a direction at right angles to the cleavage plane. There can be little doubt that the action of gravity for several hours on eggs in which normal cyclical movements have been stopped by cold does cause the heavier yolk to go down and the lighter cytoplasm and nuclei up, and this is especially true of eggs which have been injured or killed.

4. *Modifications of mitosis and cell division after return to room temperature* are found chiefly in the disorientation of amphiasters and cleavage planes Within half an hour after eggs are returned to a temperature of about 22° C. all clotting

of cytoplasm disappears and mitotic figures become more sharply defined, and they are frequently, but not invariably, turned out of their usual positions (Figs. 10, 11, 25, 37–45, 58–63, *et seq*). This disorientation of spindles and cleavage planes is the most striking after effect of cold treatment. It is evidently caused by modifications of the normal cytoplasmic movements accompanying mitosis. Study of the normal vortical movements in cell-division long ago convinced me that the spindles are turned into their usual positions by such currents (Conklin, 1902) and later work on the effects of hyper- and hypo-tonic solutions, or lack of oxygen in the water, or especially dislocations by centrifugal force confirmed this conclusion (Conklin, 1912, 1917). The present work on the effects of cold are strikingly like those produced by hypertonic solutions In both there is a loss of water from the cell and increased viscosity of the cytoplasm, in both the normal vortical movements of the cytoplasm are modified or suppressed and cell division is stopped In Crepidula neither x-rays, radium, ultraviolet, nor electric current of 200 mil amps. acting for as long as three hours has any appreciable effect on these movements and orientations.

When nuclear division is stopped by cold it is resumed when eggs are returned to room temperature but when division of the cell body has been stopped that division is never resumed When the first cleavage has been stopped two nuclei are left in the single cell body (Figs 11–13) On return to room temperature these nuclei may then resume division (Figs 14, 15) and if eggs were subjected to − 1° for about six hours, the typical second division into four macromeres may also be omitted, and two micromeres (ectomeres) may be formed at the second cleavage (Fig 16)

5. *Changes in the Number of Blastomeres with No Changes in Differentiation.*—In typical eggs there are always four equal macromeres, which give rise to three quartets of ectomeres, but in eggs in which there is only a single macromere, although this usually contains two nuclei which are the products of the first cleavage mitosis (Fig. 13), the ectomeres are formed in duets instead of quartets.

Typically, mitotic figures and the resulting cleavage planes alternate in direction in successive cleavages, the rotation of cell contents and nuclei is clockwise in the first cleavage, counter-clockwise in the second, and so on through many cleavages When both first and second typical cleavage furrows are suppressed the single macromere, with two nuclei, gives rise to three duets of ectomeres in the typical directions, the first set coming off in a clockwise direction, the second counter-clockwise, etc Even the subdivisions of these duets may be in the typical direction as shown in Figs 13–24. In some eggs one of these macromere nuclei divides a fourth time, well in advance of the other one, and gives rise to a large cell which corresponds in position and general appearance to the mesomere, 4*d*, of typical eggs (Figs 23, 24)

Other cases in which there is a single macromere with one, two, or more nuclei are shown in Figs. 25–36 When the first cleavage spindle is turned into a position oblique to the egg axis protoplasmic micromeres may be formed at the animal pole but these are always abnormal and they never continue to develop (Figs. 26, 27) Other eggs with two nuclei in the single macromere give rise to ectomeres that are more or less abnormal in position or time of division (Fig 28) while in others the macromere nuclei after giving rise to micromeres may subdivide into four, eight, or many nuclei without division of the macromere itself (Figs. 33, 35, 36). In all of these cases the differentiation of ectomeres and mesomeres from the entomere (macromere) depends upon the segregation by protoplasmic movement of different substances in the polar axis of the egg and the sizes and positions of cells depend upon cytoplasmic currents which turn the amphiasters into typical positions

A rather common disorientation is one in which the first cleavage spindle is turned into the chief axis of the egg and the resulting cell division is transverse to that axis (Figs. 37–45) Such eggs rarely segment a second time, as in Fig. 45, and they rarely develop further, although Fig 36 may be such a case It is interesting to see that in such cases the nucleus, centrosphere and cytoplasmic area in the lower cell rotate in the telophase into a position on the animal pole side of the cell (Figs. 38–40). The fact that such eggs do not generally give rise to ectomeres, as in the cases previously described, indicates that processes of differentiation are more seriously disturbed by an equatorial first cleavage than by the suppression of the typical first and second cleavages

Eggs which are in the two-cell stage when exposed to cold show many instances of clotting of cytoplasm, disorientation of mitotic figures and cytoplasmic areas, as shown in Figs. 46–63. These cytoplasmic and nuclear changes have been described in the previous section and I take up here the later cleavages of such eggs Of course, many such cleavages are very abnormal, especially when the temperature was 0° or lower or the time of exposure was prolonged Some of these abnormal cleavages are shown in Figs. 65, 82–89, and any general principles illustrated by them will be discussed later On the other hand many cleavages are perfectly normal, except that the second typical cleavage is omitted altogether (Figs 66–75) This is proved not only by the size and differentiation of the daughter cells but also by the direction of the divisions by which they are formed In the typical second cleavages into four macromeres the amphiasters are always læotropic in position (Fig *D*), but in these eggs the amphiasters are dexiotropic as they are in the typical third cleavage (Figs. 66, 67) The second typical cleavage is entirely omitted in these eggs, consequently there are only two macromeres, and the micromeres are formed in twos instead of fours, but in every other respect they are entirely typical. The contents, positions and subdivisions of these cells are precisely as in typical cleavage, except that since they are only half as numerous they are twice as large The first set of micromeres (1) comes off in a clockwise direction (Figs. 66, 67); the second (2) counter-clockwise (Figs. 68, 69, 72), the third (3) clockwise (Figs 71, 73–75) The first set subdivides unequally and in a counter-clockwise direction into a larger central (1^1) and a smaller peripheral "turret" (1^2)

cell (Figs. 69–74), and the central cells then divide in a clockwise direction (Fig. 75); the second set subdivides in a clockwise direction (Figs 73, 74) in a wholly typical manner, and one of the macromeres then gives rise to the mesomere, *4d*, in a counter-clockwise direction (Fig. 76) In all these cells, during the telophase and resting stage, the centrospheres turn into a position on the animal pole side of each cell (Fig 67) and the coarse granules over the upper aster of each mitotic figure are precisely as they are in typical cleavage (Fig 68)

All of these cases indicate that the organization of the egg and of different blastomeres precedes cell division and that differentiation does not depend upon a particular succession of cleavages nor the number of blastomeres Furthermore the segregation, localization and orientation of cell contents and of mitotic figures is caused by regular vortical movements in the cytoplasm

Of course the disorientation of these movements by low temperature frequently leads to very abnormal forms of cleavage but such abnormalities only confirm the conclusions of the preceding paragraph Divisions of the cell body may be suppressed following the division of the nucleus leaving a binucleate or multinucleate macromere, the later divisions of which give rise to abnormal numbers of micromeres (Figs. 77–79), or the typical number of macromeres may be increased (Fig 80) or decreased (Fig 81) without altering the typical form of cleavage and differentiation, although the total number of cells is altered.

Figures 82–89 are a few of the abnormal forms of cleavage caused by low temperature In these the order of some of the cleavages is indicated by Roman numerals and it is evident that profound disorientations of development have been caused. In some of these the segregation of cytoplasm toward the animal pole of each cell and of yolk toward the vegetative pole is evident, in others even this differentiation has been disturbed or disoriented in some of the cells, but none of these are inconsistent with the general conclusion already expressed that the disorientations of development caused by cold are the results of modifications of the typical protoplasmic movements within cells The probable interpretation of each of these figures 82–89 is given in the description of figures.

6 *The Later Development of Eggs Subjected to Low Temperatures.*—The development of many of these eggs was followed for as long as ten days and until larval organs had appeared. Some of those in which the second cleavage had been omitted, but the form of later cleavages was typical, except for the number of blastomeres, gave rise to normal blastulæ, gastrulæ and veligers In some the gastrulæ were elongated, but otherwise normal. Many gave rise to exogastrulæ with the shell gland, velar cells and œsophagus well formed in the ectodermal hemisphere. Partially separated blastomeres of the two-cell stage developed abnormally Some small gastrulæ and veligers were apparently normal and may have come from eggs in which the first cleavage was equatorial and the vegetative half was completely cut off In other experiments small fragments of larvæ with differentiated ectoderm cells were formed, evidently from isolated blastomeres However, such isolated blastomeres were not followed individually through their development, but there is no reason to suppose that a fragment of an egg may give rise to an entire larva On the contrary many previous experiments have proved that isolated blastomeres of Crepidula are not totipotent

Conclusions

The results of this study may be summarized as follows

1 Fertilized eggs of *Crepidula plana*, before cleavage or in its early stages, when subjected to temperatures of from − 1° to + 5° C. for from 2 to 20 hours show the hyaloplasm contracted into islands or clots, typical vortical movements of the cell contents are stopped, resting nuclei may continue to grow by absorption of fluid from the cytoplasm.

2. If eggs are left undisturbed in the refrigerator for 6 or more hours the heavy yolk tends to settle to the lower side

and the lighter cytoplasm to rise to the upper side, but this segregation is never complete. This partial segregation is probably due to the cessation of vortical movements since it does not take place at usual temperatures when such vortical movements are present

3. Low temperatures do not affect all processes of cell division and differentiation equally or simultaneously. The clotting of hyaloplasm, probably accompanied by loss of water, is the first visible effect This is associated with partial or complete suppression of vortical movements in the cell and the stoppage of cytodieresis Then follow the disappearance of spindle fibers, asters and centrosomes and the suppression of division of the chromosomes If mitosis had reached the telophase before subjection to cold, the daughter chromosomes do not form chromosomal vesicles but lie unchanged in a mass of archiplasm occupying the area of the former amphiaster. Resting nuclei and nucleoli continue to grow in the cold and may become enormous All of these modifications are similar to those caused by hypertonic solutions (Conklin, 1912).

4 Recovery from these effects, when the eggs are returned to a temperature of *ca* 22° C., is in the following order

(1) Disappearance of cytoplasmic clots (2) Reappearance of amphiasters and resumption of nuclear division (3) An interrupted cell division (cytodieresis) is never completed, but is entirely omitted; thus binucleate cells arise (4) The typical differentiations of blastomeres are more or less independent of their number and sequence, but not of their orientation with respect to the egg axis. After the first or second cleavage furrows have been suppressed they are never completed, and when the vortical currents reappear they and the orientations of the mitotic figures may be those typical of the third and all later cleavages and in that case typical micromeres (ectomeres) are formed in sets of two (duets) instead of sets of four (quartets) However, if the renewed vortical movements are atypical and the mitotic figures are turned out of their typical positions the resulting

cleavages and differentiations are atypical (5) These results indicate that various processes in cell division and differentiation may be halted by cold at different times and thus their typical correlations altered They also indicate that after the orienting movements of an earlier stage have been stopped for a time they are not resumed at the point where they were stopped, but are followed by vortical movements characteristic of a later stage, as if the factors of typical development were undergoing progressive change during the period of refrigeration, although the typical expression of those factors is suppressed.

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DESCRIPTION OF FIGURES

All figures are of whole eggs and cleavage stages of *Crepidula plana*, which had been subjected to low temperature (− 1° to + 5° C) for from 4½ to 24 or more hours They were then either fixed at once and then stained and mounted entire, or were kept in sea water at room temperature (ca 22° C) for periods varying from 1 to 24 hours before being fixed, stained and mounted

All figures were drawn with the aid of a camera lucida under Zeiss 3 *mm* oil immersion, ocular 4, at table level (magnification *ca* 550 dia), in the process of reproduction they have been reduced by about ⅓ so that they are magnified about 350 dia as here represented

In all eggs that were kept at − 1° to + 5° C for one hour or more and then fixed at once, the cytoplasm throughout the yolk area is clotted or contracted into islands and strands, this clotting disappears within an hour when eggs are brought back to room temperature, but cytoplasm and mitotic figures are frequently dislocated from their normal positions It should be emphasized that the eggs and cleavage stages shown in these plates are only a few of the innumerable forms of abnormalities caused by cold The figures selected for reproduction here are those which could be most readily interpreted in terms of normal development

PLATE I

FIG 1 Egg in first maturation metaphase with the upper aster attached to the surface at the animal pole, which is drawn in at this place The unusually thick layer of peripheral cytoplasm over the vegetative half probably indicates that this side was uppermost while in the cold chamber, islands and strands of cytoplasm are found throughout the yolk, the sperm nucleus (♂N) lies near the equator in a strand of cytoplasm leading from near the vegetative pole to the maturation spindle, 0° for 6 hrs, fixed at once

FIG 2 Metaphase of second maturation division, spindle tangential to surface, sperm nucleus (♂N) at periphery near equator, no sperm aster evident, clots of cytoplasm in the yolk and a central line of such clots through the axis of the egg, the egg surface is wrinkled, indicating that the egg has lost water, − 1° for 8 hrs, fixed at once

FIG 3 Anaphase of second maturation (2d mat), spindle greatly elongated, sperm nucleus and aster (♂N) below equator, polar lobe (*PL*) at vegetative pole, from which an axial path of cytoplasm runs up to the maturation spindle, clots of cytoplasm throughout the yolk, − 1° for 6 hrs, fixed at once

FIG 4 Telophase of second maturation, egg chromosomes and aster (♀ *Ch* & *A*) in a semi-circular group at the animal pole, second polar body under the first, which has divided, sperm nucleus and aster widely separated near center of egg, polar lobe (*PL*) at vegetative pole, − 1° for 6 hrs, then room temp 22 hrs, development permanently halted

FIG 5 Resting egg nucleus at animal pole, sperm nucleus (♂N) in center in a path of cytoplasm leading from the animal to the vegetative pole, the latter marked by the polar lobe, no clots of cytoplasm in the yolk, − 1° for 6 hrs, room temp 1 hr

FIG 6 Egg kept at 1° C for 52 hrs and then fixed at once The principal mass of hyaloplasm (*Hy*) and the chromosomes of the egg nucleus (♀ *Ch*) are near the vegetative pole, probably owing to the long-continued action of gravity on an inverted egg, sperm nucleus (♂N) and spheres (*Sp*) near equator, cytoplasmic clots and strands are roughly radial

FIG 7 Giant second polar body containing two karyomeres, first polar body dividing, large egg nucleus (♀*N*) and aster (♀*A*) at the animal pole and an equally large sperm nucleus (♂N) and aster (♂A) at the vegetative pole, − 1° for 6 hrs, room temp 22 hrs Movements of nuclei and asters and formation of cleavage spindle have been stopped

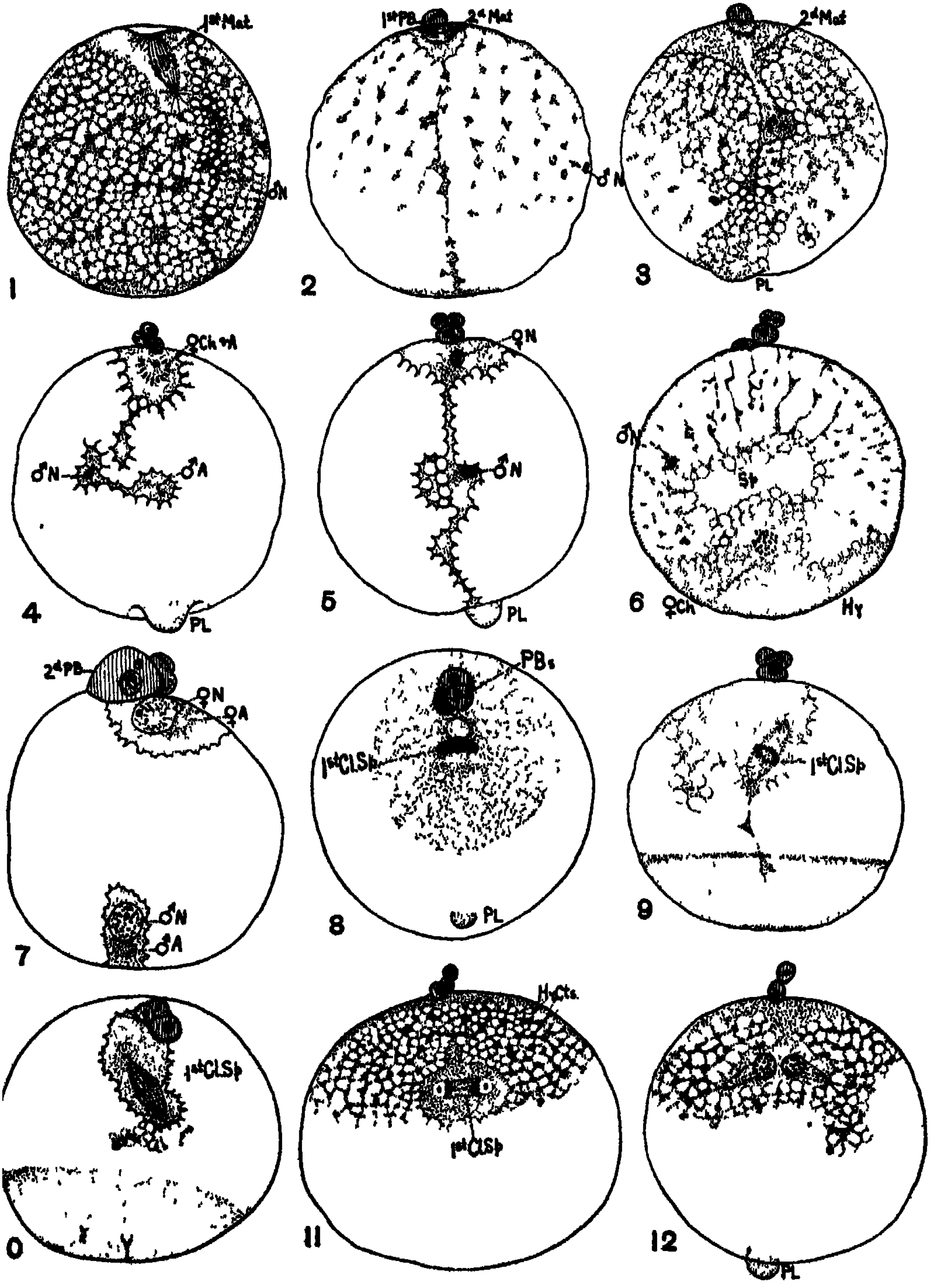
FIG 8 First cleavage spindle nearly vertical in the egg axis, which is marked by the three polar bodies (*PBs*) and the polar lobe (*PL*), 0° for 6 hrs, room temp 1 hr, during which time the cytoplasmic clots have disappeared, but the first cleavage spindle has not turned into its normal position at right angles to the egg axis

FIGS 9 and 10 Eggs of the same stage and experiment as Fig 8, but in which a thin layer of cytoplasm covers the vegetative half, presumably because of the slow action of gravity on eggs which had the vegetative pole uppermost The first cleavage spindles are oblique to the egg axis, owing to the interruption of orienting currents in the cytoplasm, 0° for 6 hrs, room temp 6 hrs, during which the cytoplasmic clots have disappeared

FIG 11 Anaphase of first cleavage spindle, which is in normal position, the thickened layer of cytoplasm at the animal pole indicates that this side was uppermost while the egg was in the cold, clots of hyaloplasm (*Hy Cts*) in the yolk, − 1° for 8 hrs, then fixed at once

FIG 12 Telophase of first cleavage, in which the daughter chromosomes have formed vesicular nuclei, but no indication of cell division is present, the spindle remnants are unusually long at this stage and clots of cytoplasm are found in the yolk, − 1° for 8 hrs, then fixed at once.

PLATE I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♂N
1
1st PB
2d Mat
♂N
2
2d Mat
PL
3
♀Ch+A
♂N
♂A
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♀N
♂N
PL
5
♂N
Sp
♀Ch
Hy
6
2d PB
♀N
♀A
♂N
♂A
7
PBs
1st Cl Sp
PL
8
1st Cl Sp
9
1st Cl Sp
0
Hy Cts.
1st Cl Sp
11
PL
12

PLATE II

FIG 13 First cleavage furrow suppressed, but its position (*1st Cl P*) indicated by a deeper staining line of cytoplasm, daughter nuclei (*N*) and asters (*A*) enormous, showing that cold does not stop their growth, cold room (*ca* 0°) for 6 hrs , room temp 4 hrs

FIGS 14 and 15 First cleavage furrow suppressed, but indicated by line of cytoplasm, second cleavage spindles present but not in normal positions, same preparation as Fig 13

FIG 16 Egg in which the first cleavage furrow was suppressed, but the nucleus divided, leaving both daughter nuclei (*M*) in the one macromere At the second cleavage each of these nuclei divided, giving rise to two micromeres of the first set (1) which are not in contact, connected with each of the four nuclei is a centrosome (*A*), – 1° for 6 hrs , room temp 6 hrs

FIGS 17–21 Same preparations as Fig 16, showing formation of micromeres in sets of twos from the single macromere containing two nuclei In Fig 17 the first set of micromeres (1) has sub-divided in normal manner into a larger central (1^1) and a smaller peripheral "turret" cell (1^2) as indicated by the bonds, the micromeres of the second set (2) have come off in a læotropic direction, as in normal eggs, and the spindles shown in dotted outline at a lower level in the macromere are dividing to give rise to two micromeres of the third set

FIG 18 All three sets of micromeres have been given off from the single macromere with its two nuclei (*MM*), the dotted transverse line indicates the position of the suppressed first cleavage furrow The two nuclei in the macromeres are labelled *M* and lie under the spindles in the central cells (1^1), the latter are now dividing a second time, having given off the "turret" cells (1^2) at their first division, as indicated by the bonds The second set of micromeres (2^1, 2^2) have divided normally, as indicated by the bonds, and those of the third set (3) have formed in the normal direction, as shown by the bonds All of these micromeres are in sets of twos, since the typical first and second cleavage furrow were suppressed and the two daughter nuclei of the first cleavage are left in an undivided egg cell, while the second typical cleavage into four macromeres is omitted entirely

FIG 19 Another egg from the same slide as the preceding, showing the micromeres of the first, second and third sets, perfectly normal in relative positions, but approximately twice the size of normal micromeres since they are present in twos instead of fours, owing to suppression of the first and second cleavage furrows and the presence of two nuclei (*M*) in the undivided macromere The first set of micromeres (1) divided first into an apical (1^1) and an outer "turret" cell (1^2), as indicated by the bonds, and the apicals are now dividing again in typical dexiotropic direction ($1^{1\,1}$, $1^{1\,2}$), the second set (2) has subdivided in læotropic direction (2^1, 2^2), while the third set (3) has not subdivided

FIG 20 A side view of an egg from the same slide as the preceding, the two nuclei in the macromere (marked *M*) are shown in dotted outline under one micromere of the third set (3), the spindle on the left is in a micromere of the second set (2), and the two cells on the right (2^1, 2^2) are also of the second set, the remaining six micromeres are of the first set, as indicated by the labels

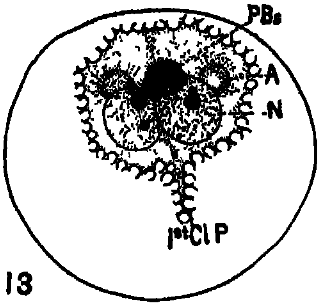
FIG 21 Apical view of an egg similar to Fig 20 The micromeres of the second (2) and third (3) sets meet in a polar furrow under those of the first (1) set, the subdivisions of which are indicated by bonds and labels

FIG 22 Side view of an egg like Fig 19 with 1 macromere containing two nuclei (*M*) and 12 micromeres, the first, second and third sets of micromeres were formed with 2 cells in each set, but the first set has subdivided twice and the second set once, – 1° for 6 hrs , 22°, 16 hrs

FIG 23 One macromere with 2 nuclei (*M*) and 16 micromeres in three sets of two each, which have subdivided so that there are 6 of the first set, 8 of the second set and 2 of the third set, which latter are shown dividing, in addition there is 1 large cell of the fourth set corresponding to the mesoderm cell (*4d*) of typical cleavage – 1° for 4½ hrs , 22°, 24 hrs.

FIG 24 Egg similar to preceding but with a faint indication of a first cleavage furrow between the two macromere nuclei (*M*), there are 16 micromeres (only 12 are shown) and one mesomere (*4d*), – 1° for 6 hrs , 22°, 16 hrs

PLATE II



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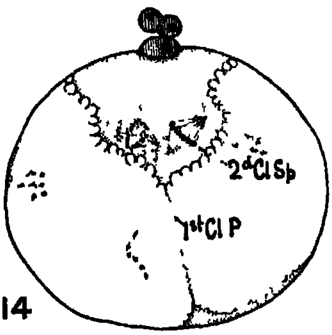

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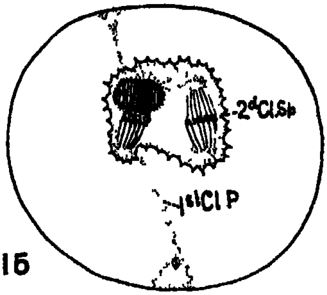

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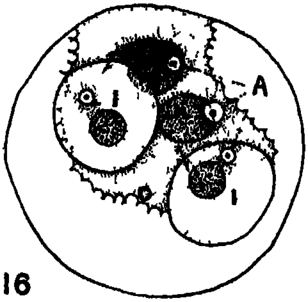

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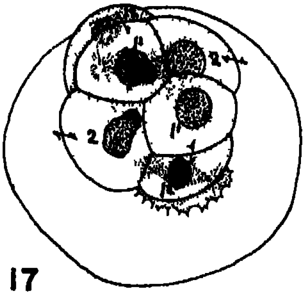

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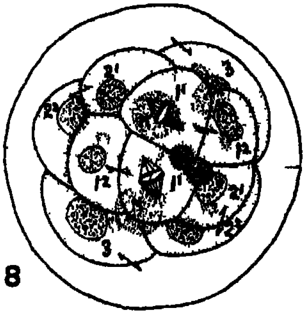

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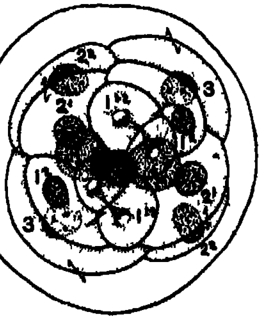

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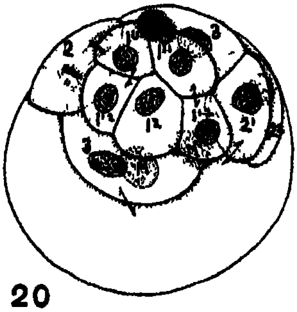

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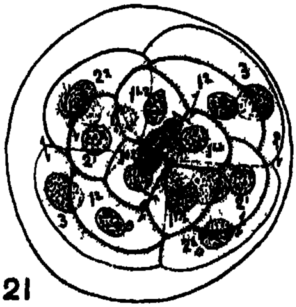

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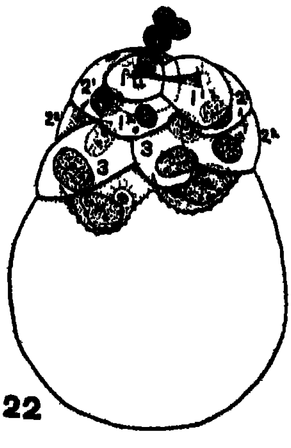

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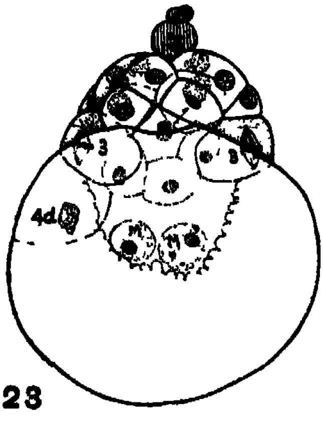

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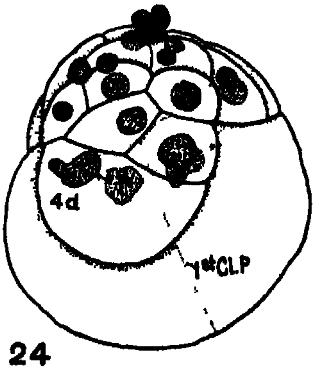

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PLATE III

FIGS 25–27 Eggs in which the first cleavage spindle was turned into a position similar to that of the 3d cleavage of normal eggs with the result that micromeres are formed at the animal pole, which are more or less similar in content, position and subsequent subdivisions to the first, second, and third quartettes of typical eggs, but in sets of ones, instead of fours Such cases are relatively rare and development is not as regular nor does it go as far as when micromeres are *formed in sets of two, as in Figs* 16–24 and 28–31

FIG 25 Giant polar bodies, first cleavage spindle oblique to egg axis, which is marked by polar bodies, polar lobe and axial path, – 1° for 8 hrs, room temp 14 hrs

FIG 26 Atypical first cleavage giving rise to a large micromere of the 1st set at the animal pole, containing a large nucleus of irregular form, two large karyomeres in the macromere have not united, – 1° for 6 hrs, room temp 16 hrs

FIG 27 The first cleavage spindle was nearly vertical and cut off a micromere like one formed typically at the third cleavage except for size This first micromere has divided unequally into a large central (1^1) and a smaller outer "turret" cell (1^2) as shown by the spindle remnant connecting the two daughter nuclei A second micromere has separated from the single macromere, as in typical cleavage, but all the chromosomes are in the second micromere and only a centrosphere is left in the macromere, – 1° for 6 hrs, room temp 16 hrs

FIG 28 Egg with one macromere containing two connected spindles, which are in process of giving off the third set of micromeres, there are six micromeres, two of which belong to the second set (2) and are in contact and not on opposite sides of the egg, as in *Fig* 17, and four belong to the first set (1^1, 1^2), – 1° for 6 hrs, room temp 16 hrs

FIG 29 Single macromere with two nuclei shown in dotted outline, and 12 micromeres, which were *formed in sets of twos*, as in *Fig* 19, *there are* 6 *of the* first set, 4 of the second and 2 of the third, same slide as preceding

FIG 30 Egg similar to the preceding with two nuclei in a single macromere and 14 micromeres, some of which cannot be identified with certainty, – 1° for 8 hrs, room temp 14 hrs.

FIGS 31–36 Eggs in which the typical first and second cleavages were suppressed and in which the micromeres cannot be identified with certainty

FIG 31 Side view of egg with one macromere containing two nuclei and with 10 micromeres, – 1° for 6 hrs, room temp 16 hrs

FIG 32 Side view of egg similar to the preceding but in which one of the two nuclei (*M*) in the single macromere is abnormal in shape and has given rise to micromeres with abnormal nuclei, – 1° for 8 hrs, room temp 14 hrs

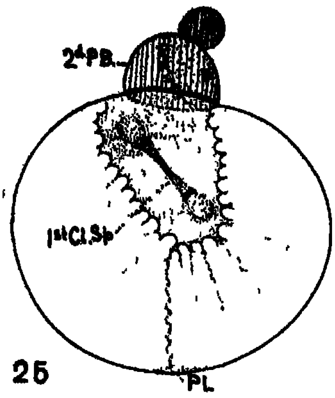
FIG 33 One macromere containing 8 karyomeres, 16 micromeres each with one nucleus, – 1° for 8 hrs, room temp 14 hrs

FIG 34 Side view of egg with two nuclei (*M*) in the single macromere and 14 micromeres, two of which are dividing, – 1° for 6 hrs, room temp 16 hrs.

FIG 35 Side view of egg similar to Fig 33, and from the same slide, in which there are 8 nuclei or karyomeres in the single macromere and 16 micromeres

FIG 36 Egg in which the first cleavage was nearly equatorial as in Figs 37–42 and in which the upper cell has given rise to 32 micromeres, the lower cell contains a large number of karyomeres, – 1° for 6 hrs., room temp 23 hrs

PLATE III



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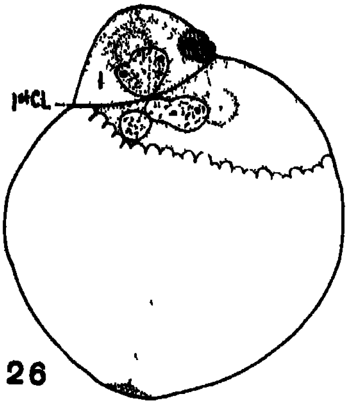

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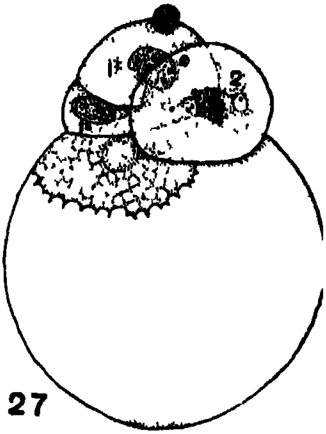

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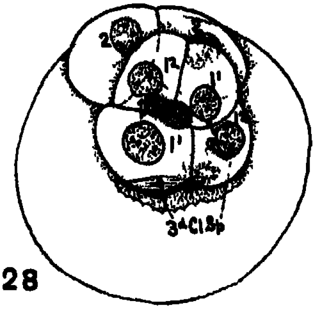

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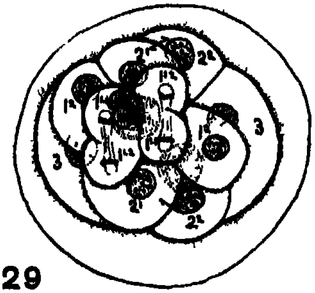

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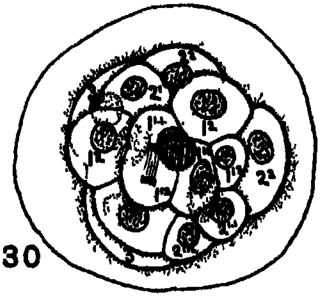

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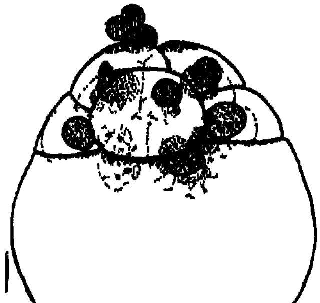

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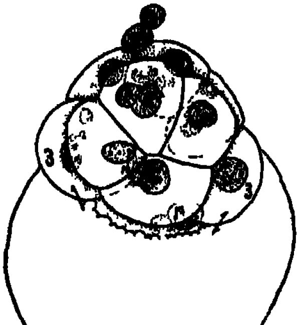

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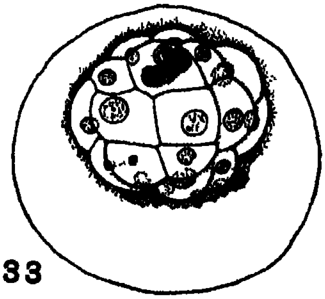

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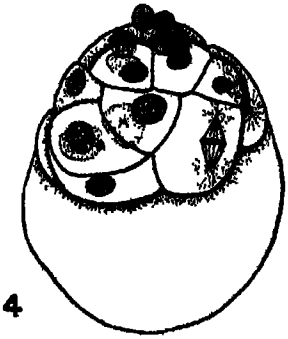

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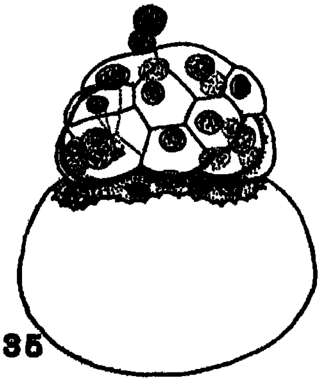

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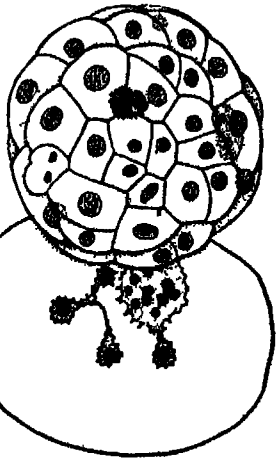

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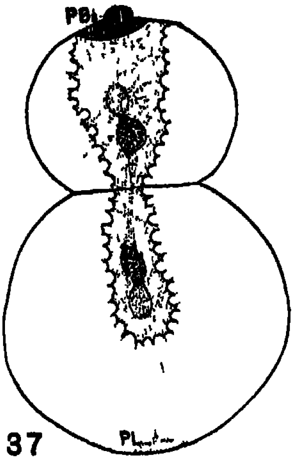
PLATE IV

FIGS 37-44 Eggs in which the first cleavage spindle was nearly vertical in the egg axis and the resulting cleavage furrow is nearly equatorial, the animal pole is marked by the polar bodies and the vegetative pole by the polar lobe or axial path of cytoplasm In Fig 37 the division wall passes through the middle of the telophase spindle, in the later stages shown in Figs 38-43 the division appears to pass through the lower end of the spindle, but this is due to later movements of cytoplasm and nuclei toward the animal pole in both daughter cells In Fig 43 the upper cell is lobulated on its lower side, the indentation lying in the direction of a meridional furrow, this probably indicates an attempt on the part of the cytoplasm to divide in the normal manner All from the same experiment, viz — 1° for 6 hrs, then room temp of 22° for 4 hrs

FIG 45 Egg in which both first and second cleavages are transverse to the egg axis, — 1° 6 hrs, then room temp 16 hrs The further development of such eggs is shown in Figs 84-88

PLATE IV



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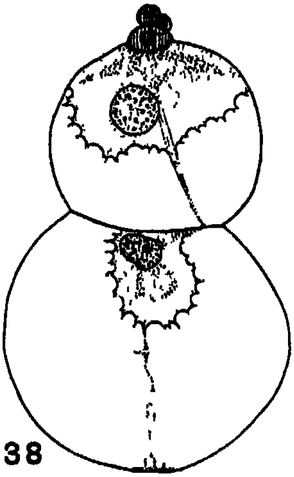

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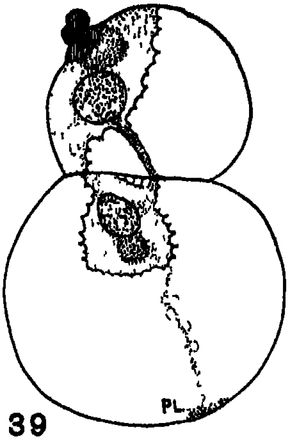

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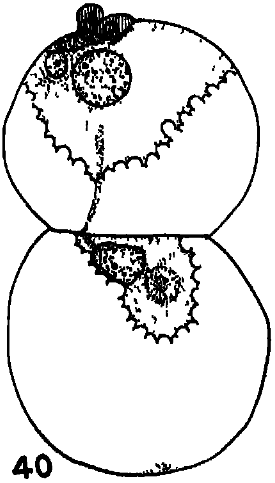

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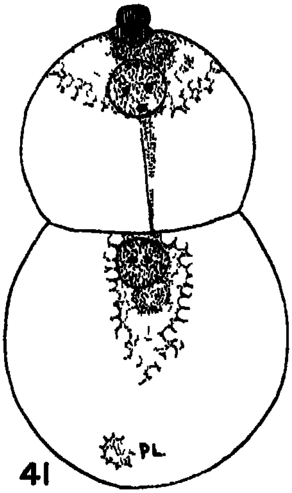

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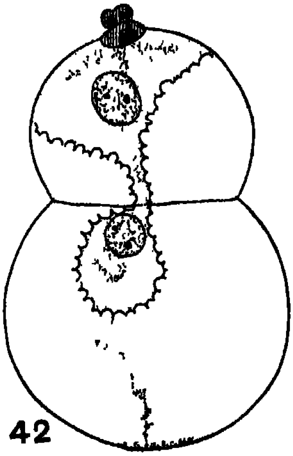

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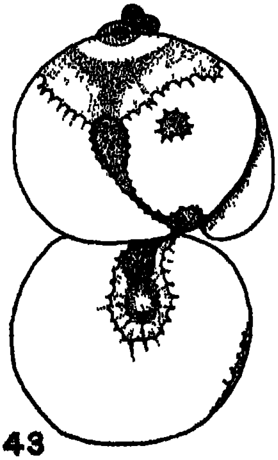

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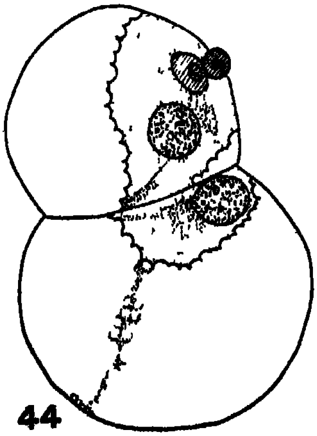

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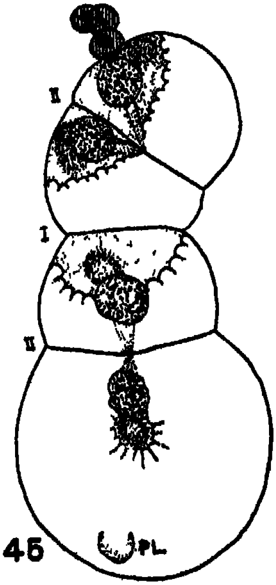

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PLATE V

FIGS 40–55 Two-cell stages subjected to – 1° to 2° C for from 6 to 23 hrs and then fixed at once All show *more or less clotting of cytoplasm* and many division stages show dislocation of mitotic figures and cytoplasm, caused by the suppression of normal movements of the cytoplasm

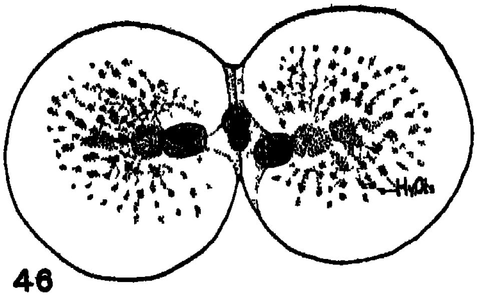
FIGS 46–48 Marked clotting of hyaloplasm (*Hy Cts*) in more or less radial lines, – 1° for 8 hrs, then fixed at once

FIG 49 Enormous nuclei and nucleoli with daughter centrospheres on opposite sides of nuclei, + 2° for 23 hrs, fixed at once

FIGS 50–51 Nuclear membrane dissolved but contents still visible with chromosome plates and centrospheres in more or less abnormal positions within the nuclear areas, + 2° for 6 hrs, fixed at once

FIGS. 52–55 Chromosomes, centrospheres and cytoplasm in abnormal positions, cytoplasm especially abundant in cleavage furrow, + 2° for 6 hrs, fixed at once

PLATE V



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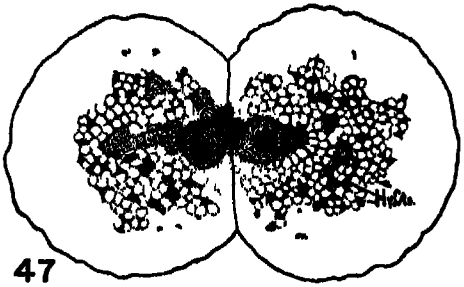

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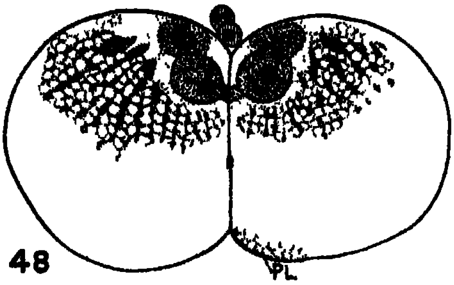

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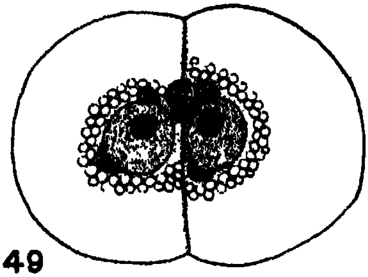

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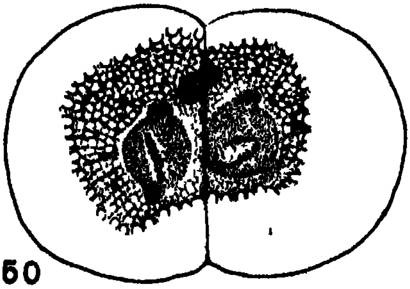

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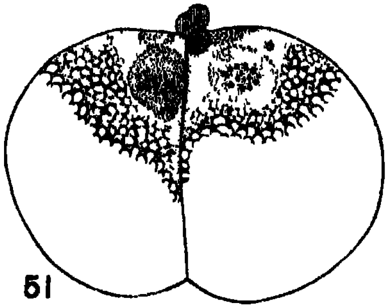

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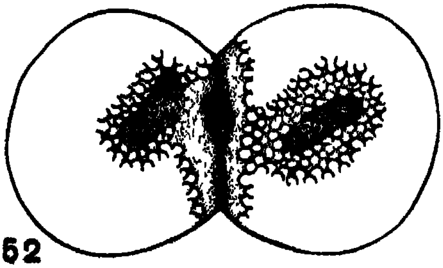

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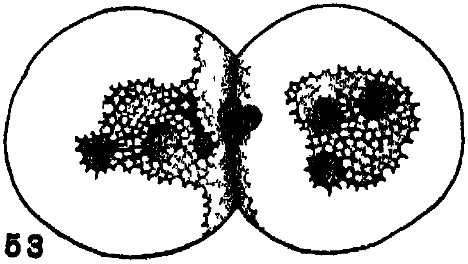

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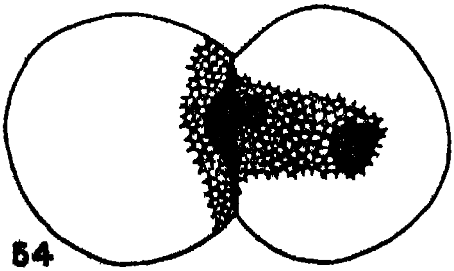

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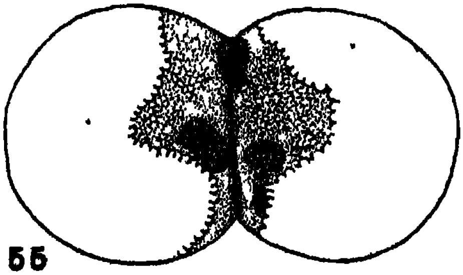

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PLATE VI

FIGS 56–63 Two-cell stages with mitotic figures in abnormal positions

FIGS 56, 57 Eggs kept at − 1° for 8 hrs and then fixed at once

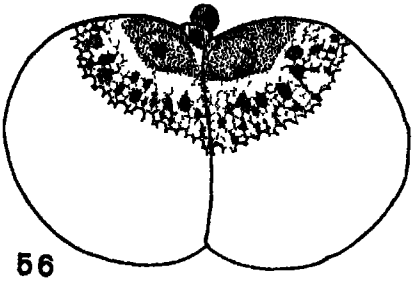
FIGS 58, 60–63 Eggs kept at − 1° for 6 hrs, room temp 1 hr

FIG 59 Egg kept at − 1° for 6 hrs, room temp 14 hrs

FIG 64 Egg kept at + 2° for 23 hrs, then fixed at once Second cleavage furrows were suppressed but nuclear division was completed and daughter nuclei and nucleoli have grown to a large size while in the cold In the right blastomere the position of the spindle was abnormal

FIG 65 Two-cell stage kept at − 1° for 8 hrs, room temp 14 hrs The second cleavage spindles were at right angles to their normal positions as in Fig 61 Cytoplasm is most abundant in the daughter cells to the right, possibly owing to the action of gravity

PLATE VI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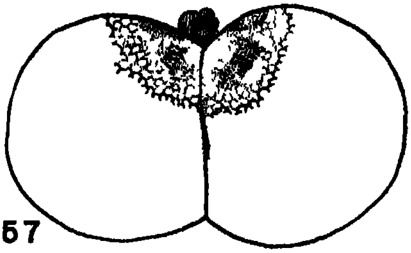
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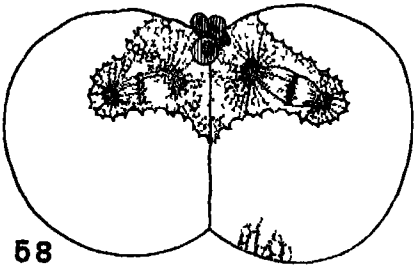
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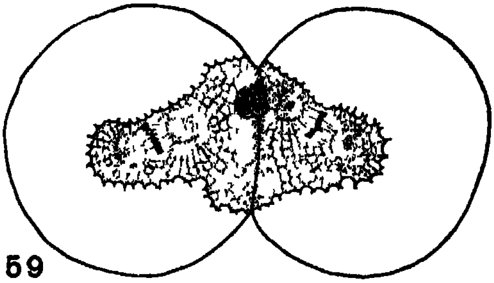
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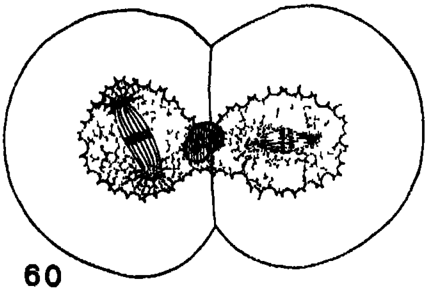
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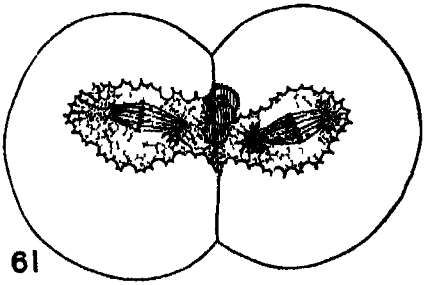
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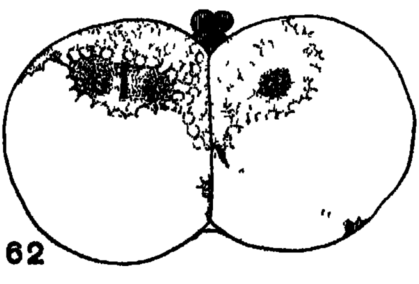
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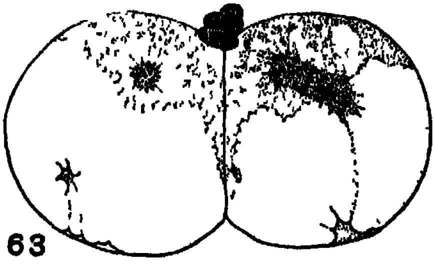
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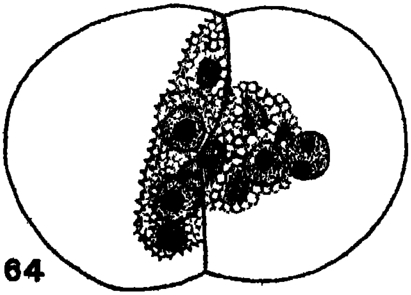
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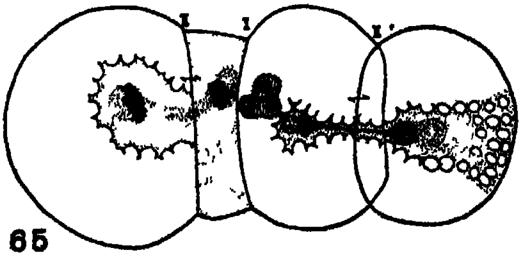

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PLATE VII

FIGS 66–75 Eggs subjected to cold in the 2-cell stage after the first cleavage was completed The typical second cleavage was entirely omitted and there are consequently but two macromeres, each of which gives rise to micromeres that are entirely typical in contents, positions and sub-divisions, but since they are only half as numerous as in typical eggs they are twice as large

FIG 66 Two-cell stage kept at 0° for 4½ hrs, room temp 24 hrs. The first set of micromeres (1) were formed by a dexiotropic direction as in the typical third cleavage

FIG 67 Side view of egg like Fig 66, granular sphere substance at apical surface of first set of micromeres, material of the polar lobe shows at the lower pole of the left (posterior) macromere, − 1° for 4½ hrs, room temp 14 hrs

FIG 68 Second set of micromeres forming in læotropic direction, as in the typical fourth cleavage, coarse granules of sphere substance at the upper ends of the spindles as in normal eggs, 0° for 4½ hrs, room temp 24 hrs

FIG 69 First micromeres subdividing in læotropic direction, nuclei and spheres in second micromeres and macromeres perfectly normal in position, − 1° 6 hrs, room temp 14 hrs

FIG 70. Side view of egg similar to Fig 69, one of first micromeres subdividing in typical manner, polar lobe at lower side of left (posterior) macromere, same experiment as Fig 69

FIG 71 Side view of stage like Fig 74, in which the first and second micromeres have subdivided and the third has formed, same experiment as preceding

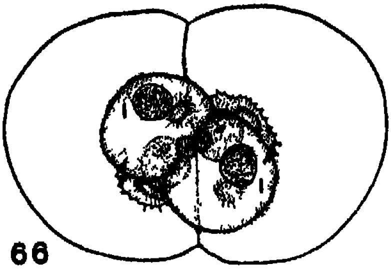
FIG 72 Apical view of stage a little older than Fig 69 in which the first micromeres have subdivided into a large apical (1^1) and a small peripheral "turret" cell (1^2), 0° for 4½ hrs, room temp 24 hrs

FIG 73 The third micromeres have been cut off in a dexiotropic direction, while the second are subdividing, all in typical manner, − 1° for 6 hrs, room temp 14 hrs

FIG 74 All three sets of micromeres present in typical positions and shapes, but double in size and half the number of those in typical eggs, − 1° for 6 hrs, room temp 22 hrs

FIG 75 Second subdivision of first micromeres in dexiotropic direction, other micromeres as in Fig 74, − 1° for 6 hrs., room temp 16 hrs

PLATE VII



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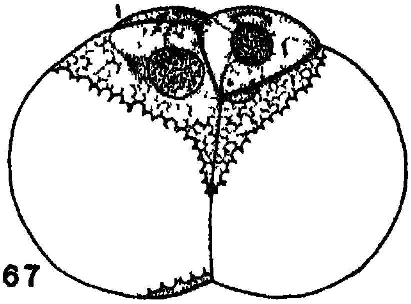

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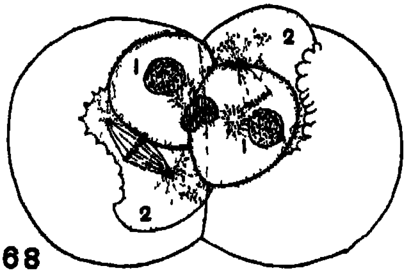

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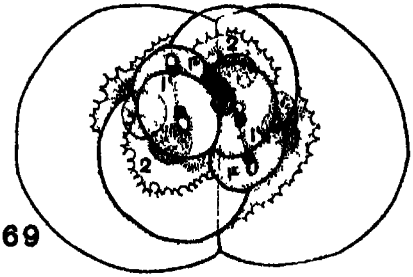

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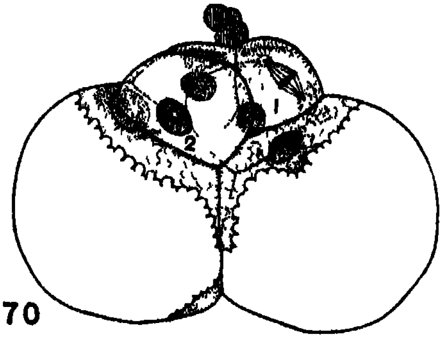

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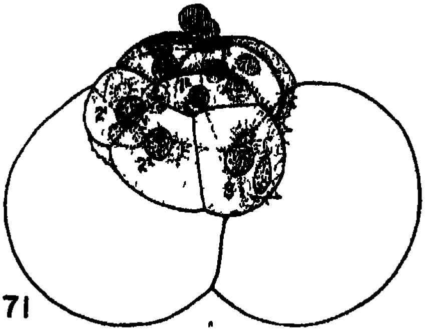

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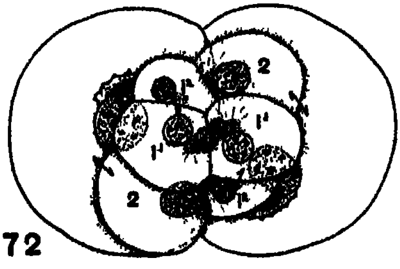

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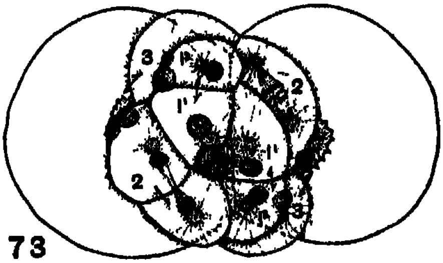

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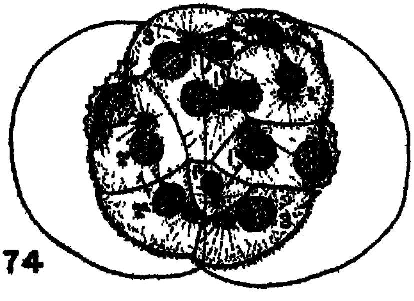

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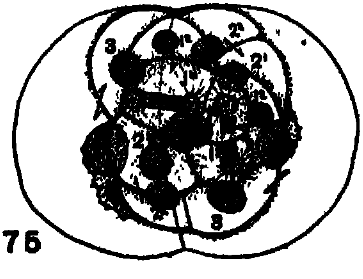

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Plate VIII

Figs 76–79 Eggs subjected to cold in the 2-cell stage in which the typical second cleavage was omitted, but in which the micromeres are not entirely typical in position or order of formation and subdivision

Fig 76 First, second and third micromeres are typical (as in Fig 74) but a large fourth micromere (*4d*) has separated from the right macromere in a *dexiotropic* direction, and *before* the second subdivision of the apical cells, − 1° for 6 hrs , room temp 23 hrs

Fig 77 Egg with three large nuclei in the right macromere and with 18 micromeres which cannot be individually identified, − 1° for 6 hrs , room temp 23 hrs

Fig 78 Side view of stage like Fig 77 with micromeres crowded down into the furrow between the macromeres, same preparation as Fig 77

Fig 79 First two macromeres widely separated with numerous micromeres between them, 1° for 24 hrs , room temp 10 hrs

Fig 80 Egg with 5 macromeres and 22 micromeres, each of the macromeres has just divided, forming 5 micromeres of the third set (3), 1° for 24 hrs , room temp 10 hrs

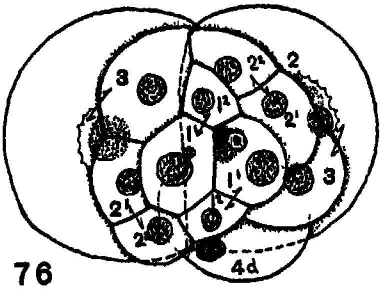
Fig 81 Egg with 3 macromeres, each of which has given off three micromeres, the micromeres of the first set have subdivided once into apicals (1^1) and small "turrets" (1^2), two of the second set are subdividing and the third set is just coming off from each of the macromeres, absolutely typical except that all are in threes instead of fours, − 1° for 6 hrs , room temp 23 hrs

Figs 82–89 Very abnormal cleavages with four or more macromeres which are abnormal in positions and subdivisions owing to dislocation of mitotic figures and cleavage planes In all these the first or second cleavage plane was transverse or oblique to the egg axis, which is marked in all cases by the polar bodies, and in Figs 87 and 89 also by the polar lobe

Fig 82 , One of the first two cleavages, probably the second (II), was transverse to the egg axis Cytoplasm and mitotic figures lie on the animal pole side of each cell Coarse granules over the upper ends of the spindles in the lower cells are like the granules of sphere substance in the second set of micromeres of normal eggs (see also Fig 68)

Fig 83 Later stage of an egg similar to Fig 82 Only two cells have their cytoplasm and mitotic figures at the animal pole, in the other cells cytoplasm and nuclei are centered on an area about 90° from the polar bodies, probably the first cleavage (I) was approximately normal, the second (II) transverse to the chief axis with most of the cytoplasm below this cleavage plane, − 1° for 6 hrs , room temp 23 hrs

PLATE VIII



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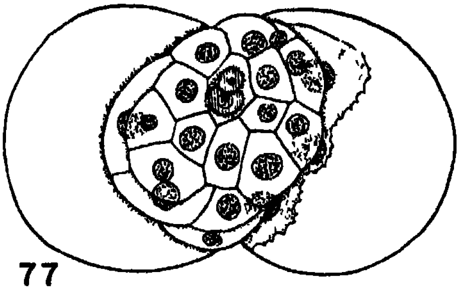

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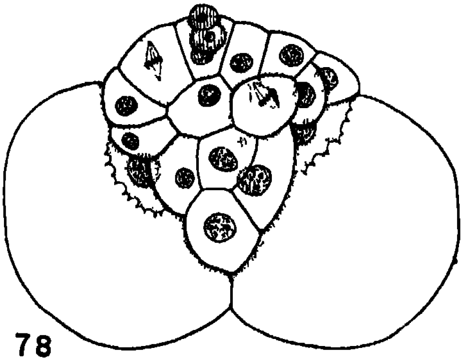

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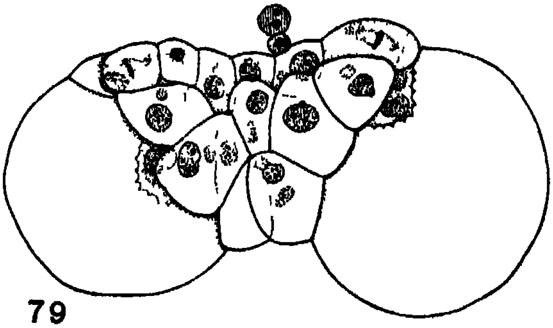

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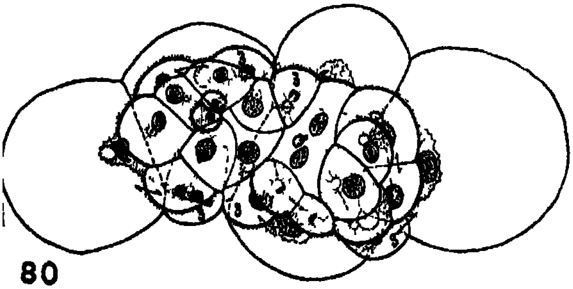

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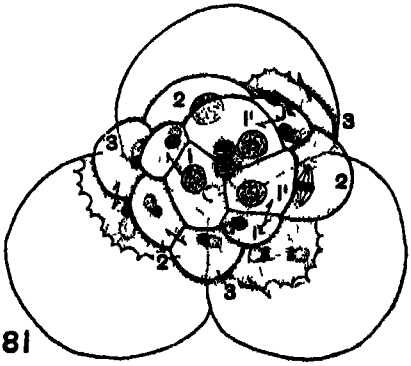

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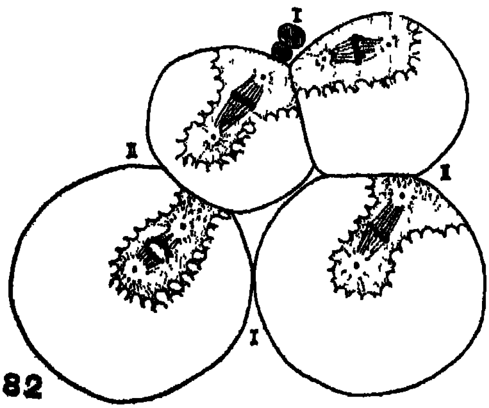

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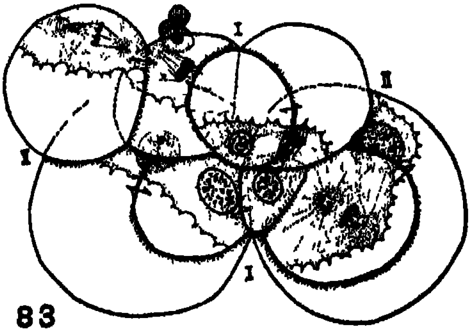

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PLATE IX

FIG 84 Abnormal 4-cell stage in which both first and second cleavage planes were oblique to the egg axis, and in which polarity is partially reversed in the right cell, possibly owing to rotation of this cell after its formation, — 1° for 6 hrs, room temp 22 hrs

FIG 85 Abnormal 8-cell stage in which the first cleavage (I) was transverse to the egg axis and the lower half then gave off two or three micromeres at its upper side while the upper half divided irregularly into four or five cells, — 1° for 6 hrs, room temp 23 hrs

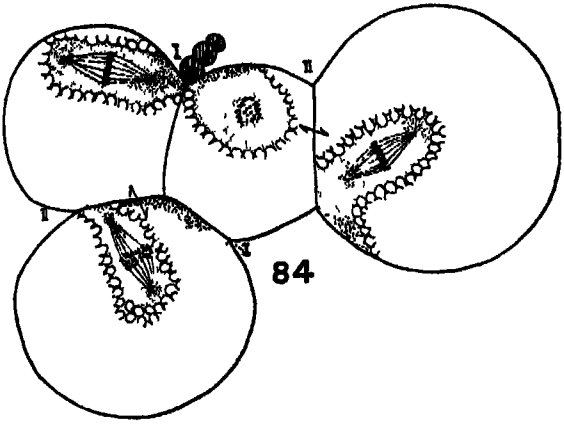
FIG 86 Very abnormal 8-cell stage in which the first (I) cleavage was approximately normal while the second (II) and third (III) cleavages were abnormal in position, — 1° 6 hrs, room temp 23 hrs

FIG 87 Seven cells (one with two nuclei, as shown by the bond) in which first, second and third cleavages were abnormal in position, the egg axis is marked by polar bodies and polar lobe substance and both first and second cleavages were transverse or oblique to this axis, — 1° for 6 hrs, room temp 23 hrs

FIG 88 Eight-cell stage in which the first cleavage (I) was nearly in the egg axis but the second (II) and third (III) were out of position (the third cleavages are marked by bonds) In spite of abnormal cleavage the cytoplasm and nuclei are on the animal pole side of each cell, showing that the intrinsic polarity of each cell is but little changed, — 1° for 6 hrs, room temp 23 hrs

FIG 89 Eight-cell stage in which the first cleavage (I) was nearly in the egg axis but the second (II) was transverse to it Each of the four macromeres so formed has given off a large micromere on its upper side and two of these micromeres are dividing, same preparation as the preceding

PLATE IX



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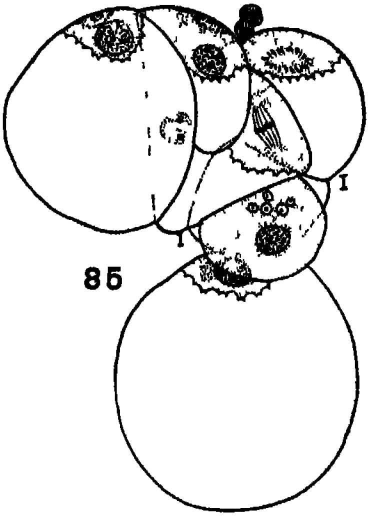

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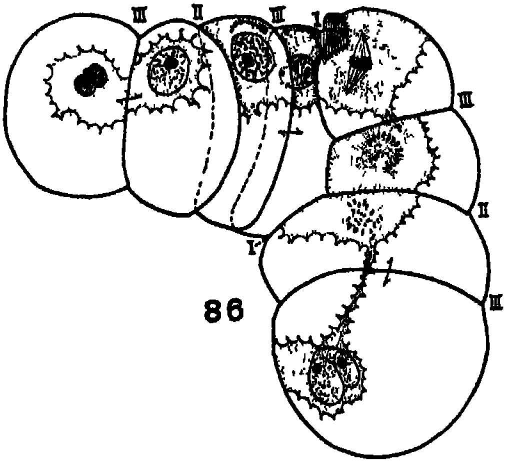

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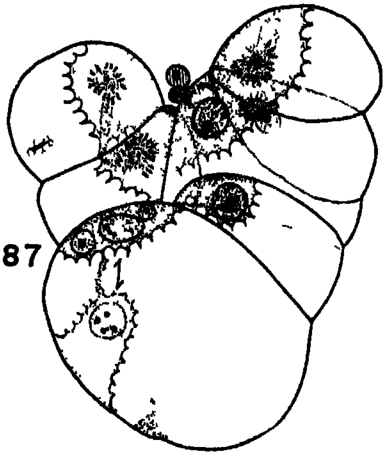

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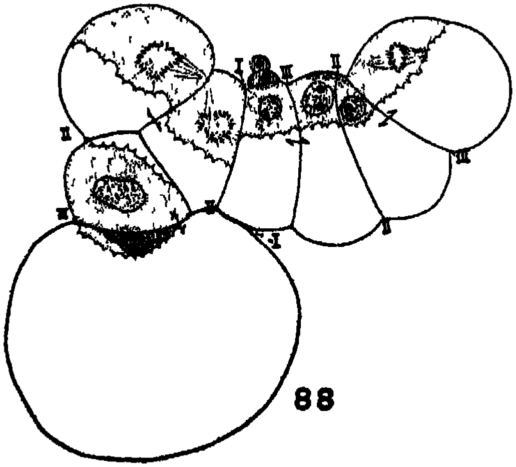

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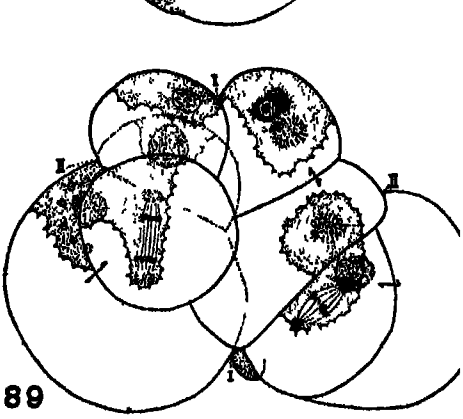

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THE AMERICAN SPECIES OF THE GENUS STENOSTOMUM

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(Communicated by Edwin G Conklin)

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ABSTRACT

Various species of *Stenostomum* have been widely used for experimental purposes but the results of the work have been confused because of the uncertainty of specific identication A review of the literature shows 30 species previously described from America, 18 of which appear to be of unquestionable validity Descriptions and plates (with specific diagnoses and a key) are furnished for these 18 and 4 new species Brief notes on the biology of the genus give a working knowledge of collection and culture methods

INTRODUCTION[1, 2, 3]

SPECIES of *Stenostomum* exhibit many characteristics which fit them well for various types of experimental work They

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[1] To Dr William A Kepner, University of Virginia, for his criticism of the manuscript and the use of his library on rhabdocoels, to Dr Alexander Vyssotsky, University of Virginia, for translating papers from the Russian and to Mrs J W Nuttycombe for invaluable assistance with the literature we wish to express our gratitude

[2] A substantial part of this work was done at the Mountain Lake Biological Station, of the University of Virginia during the summer of 1936 when the senior author held a research fellowship at the Station

[3] The senior author alone is responsible for the determination of species validity and for most of the material in the history of the genus

culture easily, reproduce rapidly, regenerate extensively and are so simply constructed that internal changes may be readily observed Several species have been widely used for studies of varied types Child (1901, 1902*a*, *b* and *c*, 1903), Van Cleave (1929, 1934), Sonneborn (1930), Carter (1933), Kepner and Yoe (1933), Nuttycombe (1932*a*) and others have used members of the genus for studies of axial gradients, normal reconstitution, reconstitution following x-radiation, genetics, the action of vital stains, phagocytosis, and for other experimental work. It appears to us that several species of the genus are ideally adapted to studies in population problems.

The results of past work have been complicated several times by the fact that accurate specific identifications were not made. Van Cleave (1929) sharply focused attention on the effect which incorrect specific identification might have upon experimental results He found that the reconstitutional behavior of *S tenuicaudatum*[1] was like that described by Child (1903) for *S. leucops* and that the species which he (Van Cleave) identified as *S leucops* had a very different reconstitutional pattern Since that time it has become apparent that many of the specific identifications of the past have been faulty

The primary purpose of this paper is to describe the present American species of the genus so that accurate diagnosis will be possible to future workers It is not the purpose of this paper to serve as an exhaustive source of information concerning the genus. We have however attempted to locate all the literature on the genus in order that we might have a fairly complete history of the various species and in order that we might select the most important papers for citation here. We believe we have been able to obtain all the papers of real significance A few others we have been unable to locate and know only from abstracts. In our attempt to limit the length of this paper we have found it necessary to reduce all sections to a minimum and in certain sections, notably those on the history of the genus and the general biology of the genus, the space allotted is hardly consistent with the importance of the topics Even in these abbreviated sections we have tried to include sufficient material and bibliography to serve as a groundwork for one who wishes to make a detailed study

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[1] We are using the specific name *tenuicaudatum* as preferable to the original name *tenuicauda* (Graff, 1911) which has been universally used until now

BRIEF HISTORY OF THE GENUS STENOSTOMUM

Dugès (1828) described *Derostoma leucops* which was later removed to a new genus, *Stenostoma*, by O Schmidt (1848). Schmidt at this time added to the new genus a second species, *S. unicolor*, and in 1852 he added a third species, *S torneense* Schmidt (1858) placed the genus in the family Microstomeen and Schmarda (1859) placed the genus in a rhabdocoel Suborder Pharyngea, Family Derostoma. Diesing (1861) placed Stenostominea in a group, Arhynchocoelo proctucha, along with *Microstomum* and others Vejdovsky (1882) moved the genus into his new family Stenostomidae and included his two new species, *S fasciatum* and *S ignavum* Graff (1882) placed the genus in the family Microstomidae and listed the following species *S gracile*,[1] *S lemnae*,[2] *S quaternum*,[3] *S coluber*,[4] *S sieboldii*,[5] *S binum*,[6] *S unicolor*, *S ignavum*,[1] *S leucops*, and *S fasciatum* [7] Graff (1913) mentions in his bibliography for *Catenula lemnae* a *Stenostomum monocoelis* described by Schmidt (1878). The genus continued for some time in and out of the families Microstomidae and Stenostomidae Keller (1894) carried the genus in Vejdovsky's Stenostomidae whereas Plotnikow (1905 *a*, *b*) located the genus in the Microstomidae Graff (1905) set up the family Catenulidae (named for the first genus, *Catenula*, in the group) which included the genus *Stenostomum* He pointed out in this paper that the original generic name, *Stenostoma*, should be discarded for

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[1] Described as *Anortha gracilis* by Leidy, 1851

[2] Described as *Catenula lemnae* by Duges, 1832

[3] Described as *Catenula quaternum* by Schmarda, 1859

[4] Leydig, 1854

[5] Graff, 1878

[6] Described as *Catenula bina* by Schmarda, 1859

[7] Vejdovsky, 1879

Stenostomum because of the likelihood of confusion of the former name with one used in 1810 in the Coleoptera. Graff carried the family Catenulidae into Bronn's Klassen und Ordnungen des Tierreichs (1904–1908)

Since the family Catenulidae was defined there has been little tendency to place the genus *Stenostomum* in any other family Luther (1907) discussed the reasons for reorganization of the family Catenulidae. In the family Luther placed the following genera. *Catenula*, *Lophorhynchus*, *Stenostomum* and *Rhynchoscolex*. Luther incidentally included sufficient historical material on the genus *Stenostomum* to serve as an excellent background for a study of the genus from this viewpoint. Sekera (1924) discussed the taxonomic relationships of *Catenula* and *Stenostomum* within the family Catenulidae and Reisinger (1924) sharply defined the sub-order Notandropora and discussed the history and systematic position of the Catenulidae

Graff (1913) placed the genus in the family Catenulidae which he placed in the section Hysterophora and listed, with descriptions, 15 species of *Stenostomum* which he considered to be valid His species were as follows· *S. leucops*, *S tenuicaudatum*,[1] *S caudatum*,[2] *S grande*,[3] *S gilvum*,[4] *S middendorffii*,[5] *S coluber*, *S. unicolor*, *S. ignavum*, *S fasciatum*, *S. agile*,[6] *S. langi*,[7] *S. stuhlmanni*,[4] *S. bicaudatum*,[8] and *S sieboldii*. It will be noted that 4 of the species in Graff's 1882 list are missing from the 1913 list, namely: *S lemnae*, *S quaternum*, *S. gracile* and *S binum*. These species in 1913 fell either into the genus *Catenula*, as then defined, as species or into synonymy within it. *S. torneense* and *S. neoboracense* [9] were listed by Graff (1913) as synonyms for *S. leucops* and *S.*

[1] Graff, 1911
[2] Markow, 1904
[3] Child, 1902 *a*
[4] Bohmig, 1897
[5] Braun, 1885
[6] Silliman, 1885
[7] Keller, 1894
[8] Kennel, 1889
[9] Girard, 1893

turgidum[1] was removed to the genus *Fuhrmannia* *S hystrix*[2] is carried by Graff (1913) in a group designated as "Catenulidarum species dubiae" but according to Hofsten (1912) Keller agreed that his (Keller's) *S. hystrix* was a young annelid. Beklemichev in 1920 added *S. coluber* to the synonymy of *Rhynchoscolex*. Certainly *S. coluber* appears to belong elsewhere than in the genus *Stenostomum*. Meixner (1924) quite rightly removed *S sieboldii* from the Catenulidae. Sekera (1903*a*) believed *S ignavum* to be a spring adapted *S. leucops* and Hofsten (1912) questioned the validity of *S. langi*. *S. langi* seems to us however a valid species which was questioned by Hofsten because of the inaccurate descriptions of some details by Keller in 1894. Markow's description of *S. caudatum* seems to us insufficient to establish a species on a sound basis. The same thing holds good for Böhmig's *S gilvum* and Böhmig's *S stuhlmanni* We have in this paper treated *S. leucops* and *S. agile* in a section devoted to species which are, to us, not very sharply defined.

Our chief interest in the European species has been in connection with the establishment of the validity of the American species and not in any sense from a desire to clarify the species of Europe or elsewhere We would however like very much to see someone in Europe redescribe the European species and set them in order

Since 1913 there have appeared in the literature 26 new specific names 3 from Europe, 1 from China and 22 from the United States. From Europe Nasonov (1924) described *S tauricum* and *S. hemisphaericum* and Gieysztor (1931) described *S. arevaloi* which Nuttycombe (1932*b*) later erroneously described as a new species, *S. rhachiocaudatum*, from the United States. Tseng-Jui Tu (1934) indecisively described *S. tsinghuaensis* from China. The 22 described species from the United States are discussed in the sections on valid and questionable species.

Including the 4 new species described in this paper there appear to be 22 sharply defined species in the United States.

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[1] Zacharias, 1903.

[2] Keller, 1895.

In addition *S agile*, *S incaudatum* and possibly others, which we have included in our questionable groups, may be perfectly valid species badly in need of redescription but we have been unable to find specimens for study

TAXONOMIC POSITION AND DESCRIPTION OF THE GENUS

The latest extensive work of the Turbellaria is that of Bresslau (1933) in Handbuch der Zoologie in which the genus *Stenostomum* is placed in the family Catenulidae, sub-order Notandropora, order Rhabdocoelida. This position of the genus seems perfectly sound as the family Catenulidae is now defined

Graff (1913) placed in the genus *Stenostomum* those Catenulidae in which the statocyst and preoral furrow are absent and which usually have paired ciliated pits and colorless light refracting bodies Since that time several species have been described which lack light refracting bodies

The body is roughly cylindrical but is, as a rule, somewhat flattened ventrally In most species the body tapers at both the anterior and posterior extremities The posterior end is generally the more pointed. There is frequently a more or less distinct head region. See Fig 1 for schematic optical sections of *Stenostomum*.

The epidermis is ciliated and in most species its cells bear in their distal ends rod-shaped rhabdites

Typically the head bears on each side a ciliated pit which is embedded in, or very closely associated with, the anterior lobe of the cerebral ganglion on the respective side. The "brain" or cerebral ganglia (Fig. 2) is usually large and prominent and is composed of paired anterior and posterior lobes The anterior lobes are in some species larger than the posterior lobes. The mesial margins of the anterior lobes are usually deeply dentate. The right and left ganglionic masses are connected by a substantial transverse commissure From each ganglionic mass 2 nerves pass posteriorly. Light refracting bodies may or may not be associated with the cerebral ganglia. In some species there is a single pair of such bodies; in others

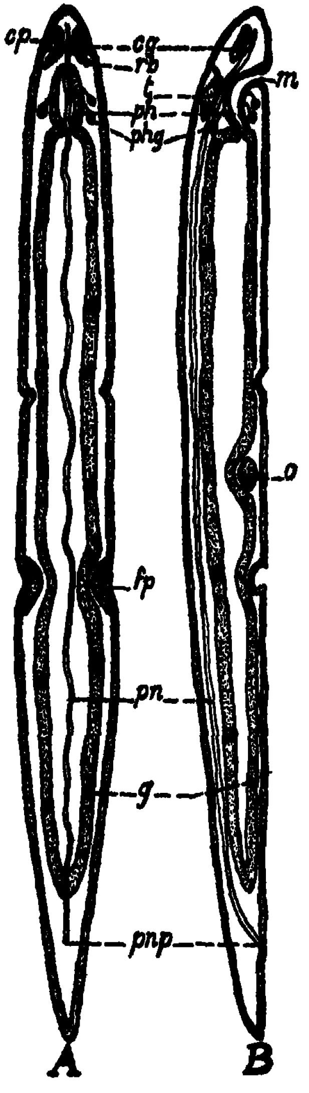

FIG 1 *A* Diagrammatic, optical view of *Stenostomum* from the dorsal side *B* Lateral view of same *cg*, cerebral ganglion, *cp*, ciliated pit, *fp*, developing fission plane, *g*, enteric "gland" cells, *m*, mouth, *o*, ovary, *ph*, pharynx, *phg*, pharyngeal glands, *pn*, protonephridium, *pnp*, protonephridiopore, *rb*, light refracting body, *t*, testis.

there may be more than one pair. The association between these bodies and the ganglia is variable in the genus but in most species they are associated with the posterior ganglionic lobes.

The mouth is located mesio-ventrally near the anterior end of the zooid. It is equipped with a sphincter (and in some cases special musculature) and opens into a simple (generally), tubular pharynx the walls of which are usually well-muscled. In many cases the outer wall of the pharynx bears unicellular glands. There may be also an elaborate radial musculature from the pharynx to the body wall. The pharynx opens posteriorly through a sphincter into the straight intestinal tube

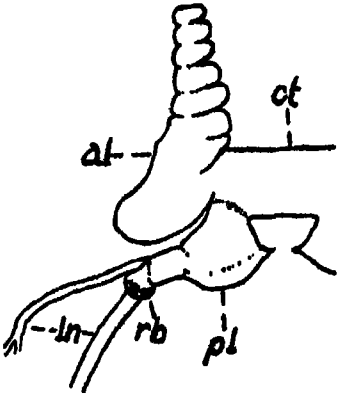

FIG 2 Dorsal view of left half of brain of *Stenostomum tenuicaudatum* *al*, anterior lobe, *ct*, transverse commisure, *ln*, lateral nerves, *pl*, posterior lobe, *rb*, light refracting body

The pseudocoel between the outer body wall, brain, pharynx, intestine, and other body parts, is traversed by radial muscle fibers and contains free cells of various shapes and sizes. The interstices are filled with a colorless plasma of undetermined consistency

The protonephridium lies in the pseudocoel and is composed of two stems. From the single posterior nephridiopore the larger tube passes anteriorly above the enteron and pharynx (except in *S. ventronephrium*) and then passes ventrally beneath the transverse cerebral commissure. Just in front of the commissure it bends upon itself to form the smaller capillary tube which passes posteriorly along the same general path as that followed by the larger tube. Reisinger (1922) and Kepner and Yoe (1933) have considered the structural and functional differences between the larger and capillary tubes of the protonephridium

Reproduction is usually asexual by transverse fission. Periodic sexual reproduction has been observed in several species. The male gonad occurs in the antero-dorsal part of the body; the ovaries in the pseudocoel near the middle of the zooid No ducts have been observed with the female gonad

METHOD OF TREATMENT OF THE GENUS

The literature reveals that 27 species have been described from America as new. As previously mentioned, Graff (1913) placed *S neoboracense* in the synonymy of *S leucops* and surely Girard's (1893) description would not justify considering *S. neoboracense* as a valid species. Beklemischev (1920) removed *S. coluber* to the genus *Rhynchoscolex*. We have already in this paper removed *S. rhachiocaudatum* to the synonymy of *S. arevaloi* and, as will appear later, we are placing *S oesophagium* in the synonymy of *S. grande*, *S. carnivorum* in the synonymy of *S virginianum* and *S. gigerium* in the synonymy of *S. tauricum*. This leaves a total of 21 previously described American species for consideration.

Some of the descriptions of these species are so imperfect as to leave grave doubt as to the validity of the species involved and in these cases we have found it difficult, if not impossible, to separate the valid from the questionable.

Our treatment of the genus is a more or less arbitrary one but we believe it will clarify the present muddle. We have set up three groups to include all the species described from or collected in the United States. The first of these groups contains only those species (*S. bicaudatum*, *S. grande*, *S. tenuicaudatum*, *S. uronephrium*, *S. virginianum*, *S. ciliatum*, *S. membranosum*, *S. simplex*, *S. mandibulatum*, *S. brevipharyngium*, *S. saliens*, *S. glandulosum*, *S. predatorium*, *S. tauricum*, *S. arevaloi*, *S. ventronephrium*, *S pseudoacetabulum*, *S. cryptops* and the 4 new species, *S kepneri*, *S tuberculosum*, *S. anops* and *S pegephilum* herein described) which we consider to be of unquestionable validity. The second group (*S. agile*, *S incautadum*, *S leucops*) consists of species which we think are possibly valid but which should be redescribed We have not attempted this because of inability to obtain specimens which fit the inadequate descriptions given. In the third group we have placed those specific names (*S. speciosum*, *S. glandiferum*, *S. giganteum*) which, to us, do not have sufficient meaning to justify serious consideration

We have included in our key only those species in the first group.

We have listed certain papers with each description and, except for *S leucops*, the lists include practically all the literature except mere collection records The literature on the American species, except that on *S. leucops* (much of which should fall into the synonymy of *S. tenuicaudatum*), is limited Our bibliographic files show references to *S. leucops* in well over 100 papers but we have listed only the major descriptive papers on this species.

Another problem which we have encountered is that of varieties. We have been culturing for several years 4 varieties of *S. tenuicaudatum* and during the summer of 1936 we observed still another variety of this species at Mountain Lake, Virginia. These varieties show fairly constant minor differences such as length of free tail region, shape of anterior end, etc , which we consider of less that specific value but which are sufficiently evident to enable us to distinguish the varieties from each other We do not believe these varieties would be easily distinguished by persons less familiar with the genus.

We have, wherever possible, redescribed or amplified the descriptions of all species which we have been able to obtain. Our descriptions are based on the study of many specimens of the species involved. We have been able to maintain cultures of some species for several years and these have shown no morphological changes in their artificial environment. A few species do not culture easily and the descriptions are based on numerous specimens from their natural environments

Descriptions or identifications should not be attempted from a few specimens lest stress be placed upon some variable feature such as enteric vacuoles, color of the enteron or prominence of granular enteric cells. Such features vary with the physiological state of the organism Gross size is another feature which shows a wide range of variability, for instance, the length of *S virginianum* ranges from 0 2 mm to 5 0 mm This range overlaps the ranges of practically all other species In short, there are many features which have very little value in specific diagnoses

We have attempted to use in our key, and stress in our descriptions, those anatomical features which are least variable and thus are of most value as specific characters. In this category we may list such features as the position and nature of the light refracting bodies, the position of the protonephridiopore, the pharyngeal structure and certain glandular bodies of the epidermis

It seems highly desirable at this point to discuss briefly the nature of some of the characteristics which we have used in our descriptions and key for the purpose of specific diagnoses.

The light-refracting element itself (Fig 3) may be a granule, plate, rod or may be composed of several such units of the same type Typically a light-refracting body has associated with it a clear or finely granular vesicle which, in turn, is usually closely associated with a portion of the cerebral ganglia. In some cases where the association of the vesicle and the ganglion is not evident it may be assumed that a nerve tract passes from the vesicle to the ganglion although casual examination does not reveal such tracts

The light-refracting bodies of different species differ as to type, number and position Von Graff (1913) recognized three types of light-refracting bodies as follows: dish-shaped, formed by many refractive spherules, shell-shaped, rounded vesicles with incompletely thickened refractive walls; and lens-like, lens-shaped or saddle-shaped refractive bodies. We have found some slight irregularities in the refractive bodies of such forms as *S. virginianum*, *S glandulosum*, *S. arevaloi*, and *S. bicaudatum*. Thus, in *S. virginianum* the refractive body may appear as a flattened triangular plate or may show such indentations as to present a tri-lobed appearance (Fig. 3, *b* and *c*) Approximately similar conditions exist in *S uronephrium* In *S. glandulosum*, *S arevaloi* and *S. bicaudatum* the

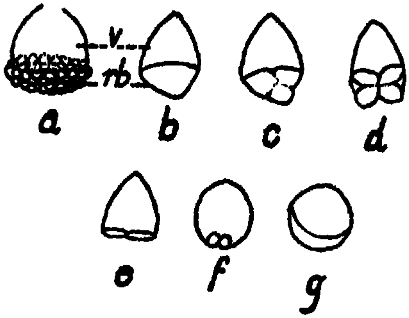

FIG 3 Varieties of light refracting bodies *v*, vesicle, *rb*, refracting unit, *a*, light refracting body of type 1 formed of many refractive spherules as in *Stenostomum tenuicaudatum*, *b* and *c*, light refracting bodies of type 2 as found in *Stenostomum virginianum*, *c* and *d*, light refracting bodies of type 2 as in *Stenostomum uronephrium*, *e*, light refracting body of type 2 as in *Stenostomum ciliatum*, *f*, light refracting body of type 2 as in *Stenostomum glandulosum*, *g*, light refracting body of type 2 as in *Stenostomum cryptops*

number and positions of the refractive spherules vary somewhat In *S cryptops* each posterior refractive body is composed of a single unit so shaped and applied to its vesicle as to give it the appearance of a shallow dish (Fig 3, *g*). The anterior body in this species is a spherule associated with a vesicle. According to Kepner and Carter (1931) *S. simplex* exhibits a pair of light refracting bodies each of which is a simple granule unassociated with a vesicle. The following scheme of classification of light refracting bodies seems better adapted to the American species than the scheme of von Graff.

1. Bodies each of which is composed of more than 10 granules or spherules so arranged over a part of the surface of the associated vesicle as to take the form of a shallow dish (Fig. 3, *a*).

2 Bodies each of which is composed of 1 to 5 granules or spherules, plates or rods associated with a vesicle or, of a single-unit, dish-shaped body associated with a vesicle (Fig 3, *b*, *c*, *d*, *e*, *f*, *g*). This single-unit, dish-shaped body would correspond to Graff's shell-shaped type with incompletely thickened wall

3. Single-granule bodies unassociated with a vesicle.

In the first group would fall such refractive bodies as those of *S. grande* and *S tenuicaudatum*, these bodies contain 20–50 granules surrounding the end of the vesicle.

In the second group would fall such bodies as those of *S. arevaloi*, *S. glandulosum*, *S virginianum*, *S ciliatum*, *S. uronephrium*, *S. cryptops*, *S. bicaudatum*, and *S kepneri*

In the third group would fall such bodies as those of *S. simplex*.

According to von Graff our first type is the more prevalent type. This does not hold for the American species among which bodies of our second type are more common

These light-refracting bodies are typically paired and vary in number from one to four pairs The position of the bodies with reference to the cerebral ganglia is variable in different species. The most prevalent condition is one in which a single pair of such bodies is associated with the posterior lobes of the cerebral ganglia. In *S. arevaloi* there are two pairs above the anterior ganglionic lobes and one pair above the posterior ganglionic lobes. In *S. glandulosum* the four pairs of refractive bodies lie above the anterior lobes, in *S. cryptops* one pair is associated with the posterior lobes and one pair with the anterior lobes and in *S. bicaudatum* the three pairs lie above the anterior ganglionic lobes.

Another feature of considerable diagnostic value is the pharynx. The pharyngeal wall may be muscular or membranous; it may be modified so as to present two or more fairly definite regions, the pharynx may be completely surrounded externally by unicellular glands or the glands may be localized, the radial musculature of the pharynx may be very elaborate or relatively undeveloped, the pharynx may contain special, evertible tentacular structures. The oral opening may have no apparent skeletal elements or it may be equipped with a tubercle-like or rod-like skeletal element on each side

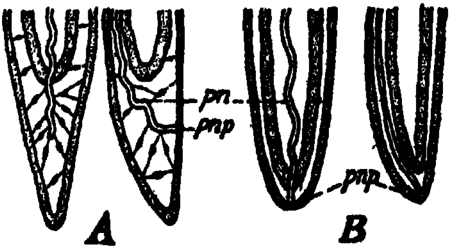

FIG 4 Diagrammatic dorsal and lateral optical views of posterior end of *Stenostomum* showing, *A*, protonephridium opening in middle of enteron-free tail region, and *B*, terminal opening of the protonephridium in a type without appreciable enteron-free tail region *pn*, protonephridium, *pnp*, opening of the protonephridium or protonephridiopore

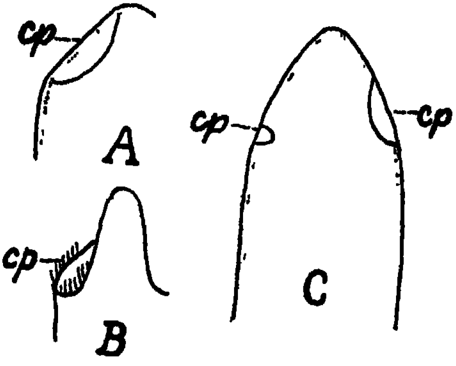

FIG 5 Types of ciliated pits *A* and *B* large anteriorly directed pits, *C*, small lateral pit on left and larger lateral pit on right *cp*, ciliated pit

The position of the posterior nephridiopore is likewise a relatively constant character It may be located terminally or slightly subterminally (Fig 4, *B*), or it may be placed more anteriorly between the end of the enteron and the posterior end of the body (Fig. 4, *A*).

The epidermal cells of most species contain more or less prominent rod-shaped rhabdites In *S arevaloi*, *S. ventronephrium*, *S anops*, *S. bicaudatum* and *S glandulosum* the epidermis contains peculiar "gland" cells and in *S predatorium* there are large glands lying just beneath the general epidermis These special epidermal features are sharply diagnostic

There are, of course, other features such as the shape, size and position of the ciliated pits (Fig 5) which are constant and which are consequently of value in specific diagnoses, but those briefly discussed above are more obvious and of more general application

Key to the American Species of the Genus Stenostomum

A *Stenostomum* with light refracting bodies	
B Light refracting bodies, a single pair	
C Light refracting bodies composed of more than 10 granules or spherules	
D Ventral surface with longitudinal tracts free of large rhabdites	*grande* (p 231)
DD Ventral surface without rhabdite-free tracts	*tenuicaudatum* (p 235)
CC Light refracting bodies composed of less than 10 granules or spherules	
D With appreciable free caudal region	
E Protonephridial opening terminal or slightly subterminal	*uronephrium* (p 249)
EE Protonephridial opening not terminal or slightly subterminal	*ciliatum* (p 241)
DD Without appreciable free caudal region	
E Protonephridial opening terminal or slightly subterminal	
F Cilia minute, light refracting bodies without vesicles	*simplex* (p 239)
FF General ciliary coat prominent, long cilia sparsely scattered over body, light refracting bodies with prominent vesicles	*virginianum* (p 257)
EE Protonephridial opening not terminal or slightly subterminal, opening typically beneath enteron	*kepneri* (p 264)
BB Light refracting bodies, more than a single pair	
C With a single, dorsally directed, caudal outgrowth	*arevaloi* (p 251)
CC With ventral and dorsal caudal outgrowths and with six evertible, tentacular fingers in the pharynx	*bicaudatum* (p 228)
CCC. Without special caudal outgrowth	
D Four pairs of light refracting bodies lying above anterior ganglionic lobes	*glandulosum* (p 243)
DD Two pairs of light refracting bodies	*cryptops* (p 262)

AA *Stenostomum* without light refracting bodies	
B Without gizzard-like unit in enteron	
C Protonephridial tube dorsal to enteron	
D Without dorsally directed, caudal outgrowth	
E Without large glandular bodies beneath epidermis	
F Epidermis without very long, prominent, stiff cilia	
G Ciliated pits small, lateral, hemispherical	*brevipharyngium* (p 238)
GG Ciliated pits large, anteriorly directed	
H Pharynx parchment-like or membranous	*membranosum* (p 240)
HH Pharynx not parchment-like or membranous, with tubercle-like body on each side of mouth	*mandibulatum* (p 242)
GGG Ciliated pits medium or large, not anteriorly directed	
H With epidermal "rosette" bodies	*anops* (p 266)
HH Without epidermal "rosette" bodies	*pegephilum* (p 269)
FF Epidermis bearing very long, prominent, stiff cilia	
G With short, distinct tubercle from ventral margin of anterior tip	*tuberculosum* (p 267)
GG Without tubercle associated with anterior tip	*saliens* (p 245)
EE With large, glandular bodies beneath epidermis	*predatorium* (p 246)
DD With dorsally directed caudal outgrowth	*psuedoacetabulum* (p 260)
CC Protonephridial tube posterior to pharynx ventral to enteron . .	*ventronephrium* (p 254)
BB With gizzard-like unit in enteron	*tauricum* (p 237)

DESCRIPTIONS OF SPECIES [1]

Species of Unquestionable Validity

S. bicaudatum Kennel (Pl. VII, Fig. 2)

Kennel, 1889, Martin, 1908.

This species was described by Kennel (1889) from Trinidad. Martin (1908) described it under the name *Weldonia*

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[1] Type specimens are located in the collections at the University of Virginia and at the University of Georgia At the University of Virginia *S ciliatum*, *S membranosum*, *S simplex*, *S mandibulatum*, *S brevipharyngium*, *S saliens*,

paraguayensis from South America but Luther (1908) shortly pointed out that the latter name should be relegated to synonymy.

We collected this species in large numbers about ten miles south of Valdosta, Georgia in roadside ditches. It has not been described before from North America.

Kennel's description is none too accurate but leaves no doubt as to the species with which he was dealing. We are completely redescribing the species without reference to the many corrections and additions we have made.

The maximum observed length for a specimen of 9 zooids was 7 mm. The body is heavy and thick but tapers sharply near the posterior end. Single zooids when contracted are almost spherical. There is a slight dorsal flattening. The posterior end bears two caudal outgrowths—the dorsal outgrowth is thicker and shorter, the ventral outgrowth delicate and long and is dragged after the animal. The ventral outgrowth is well-muscled and may be contracted considerably.

The epidermis, like the rest of the body, is faintly brownish. The enteron is dark and stands out prominently.

The general ciliary coat, composed of cilia of a length slightly greater than the epidermal thickness, is uniform except over the anterior end where it seems shorter and in the two narrow rhabdite-free tracts where the cilia are very fine and very active.

The short, rod-shaped rhabdites are confined to the distal ends of the epidermal cells. Rhabdites are uniformly distributed over the surface of the body except for a narrow rhabdite-free tract on each side of the mid-dorsal line. These tracts extend from the anterior end and converge at the tip of the dorsal outgrowth. Distributed over the body in the epidermis are special epidermal bodies like those of *S. arevaloi*. These bodies are not found in the mid-dorsal band bordered by the outer margins of the rhabdite-free tracts.

S. tauricum (as *S. gigerium*), *S. grande* (as *S. oesophagium*), *S. glandulosum*, *S. predatorium*. At the University of Georgia *S. bicaudatum*, *S. tenuicaudatum*, *S. virginianum*, *S. ventronephrium*, *S. uronephrium*, *S. arevaloi*, *S. pseudoacetabulum*, *S. cryptops*, *S. kepneri*, *S. pegephilum*, *S. tuberculosum*, *S. anops*

The cephalic ganglia conform to the generic pattern

The light refracting bodies are 3 pairs and in general are like those of *S arevaloi* The anterior pair is generally composed each of a single spherule—the second pair close behind these, is also each composed of a single spherule. The posterior pair (each of 2 or 3, rarely 4 spherules) is considerably separated from the two anterior pairs and is more lateral in position Each of the 3 pairs of refractive bodies has associated with it a clear vesicle They all lie above the anterior ganglionic lobes

The ciliated pits are large and deep and lateral in position.

The mouth is medioventral in position and is a longitudinal slit at the level of the posterior margins of the ciliated pits.

The pharynx is an extremely long tube when the animal is extended Its intrinsic musculature is well developed We have seen no cilia in its lumen The radial musculature of the pharynx is extremely elaborate especially on the dorsal side The distal ends of the fibers are inserted well anteriorly (especially those of the antero-dorsal end of the pharynx) A peculiar feature of the pharynx is an organ (called by Kennel a "grasping organ") bearing six finger-like, or tentacle-like, structures on its anterior face The posterior end of the organ appears to be in the shape of two half-spheres (or a sphere with a groove) each of which bears on its anterior face three tentacular structures The rounded base of this organ seems to be attached to the dorsal wall of the pharynx and when the pharynx is contracted the tentacles are spread as they are pushed from the mouth The spherical posterior face of this organ is covered by long-necked, unicellular glands. Internally each tentacle appears to be composed of a series of spherical cells Kennel (1889) suggested that these tentacles serve in the capture of food but we have not observed their use for this purpose, though it seems Kennel's conclusion is probably justified. The wall of the pharynx is apparently without glands.

The enteron extends posteriorly to the base of the ventral outgrowth. There are few gland cells in the enteric wall and these are not at all prominent

The cells of the pseudocoel are of various sizes and for the most part are highly refractive

The prominent protonephridium follows the usual path and opens dorsally at the base of or near the middle of the dorsal outgrowth. In most specimens granular secretions may be seen within the lumen of the tube level with the pharynx

We have been unable to culture this species satisfactorily

Specific diagnosis 3 pairs of light refracting bodies, 2 caudal outgrowths, an evertible structure bearing 6 tentacles associated with the pharynx, 2 rhabdite-free tracts on the dorsal surface.

S grande Child (Pl V, Fig 1)

Child, 1902*a*, 1903, Graff, 1911, 1913, Van Cleave, 1929, Kepner and Carter, 1931, Carter, 1933, Kepner, Carter and Hess, 1933, Kepner and Yoe, 1933, Nuttycombe and Waters, 1935*c*.

This species appears to be rather widely distributed According to the literature it has been collected in New York, Massachusetts, Illinois and Pennsylvania We have collected it in Virginia but have not been able to find it in North Carolina or Georgia Nasanov (1925) and Steinboch (1932) have recorded this species from Russia

Stenostomum grande was first described by Child (1902*a*) It has since been described by Kepner and Carter (1931) as *S oesophagium.* Kepner and Carter (1931) state that the "oesophageal region" of the pharynx is constant in *S oesophagium,* whereas, it is a variable region in *S grande,* further *S. oesophagium* is always sexually mature (testes always present), whereas, *S grande* becomes sexually mature during the autumn. Kepner, Carter and Hess (1933) later found sexuality did not occur in nature in *S oesophagium* in the early autumn.

Our reasons for rejecting *S oesophagium* as a valid species are as follows: We have maintained cultures of *S. oesophagium,* always sexually mature as males, for 4 years and have examined them repeatedly to determine whether or not the "oesophageal region" is a constant definite region. In old specimens we have frequently found this region thrown into folds such as Child described for this part of the pharynx of his *S grande*. We have also studied carefully a species collected at Mountain Lake, Virginia, identified as *S. grande*, which did not show gonads We perceive no constant appreciable differences between this *S. grande* and *S. oesophagium* with reference to the "oesophageal region" or to any other feature. Further, we believe as has already been pointed out by Sekera (1903*b*), Nuttycombe (1931) and Kepner, Carter and Hess (1933), environmental conditions to be a major factor in sexuality in *Stenostomum* and we see no reason for assigning specific differences to the presence or absence of gonads at any particular time if these gonads do not differ structurally when they do appear. As a point of interest, it may be noted that the *S. oesophagium* cultured for several years by Kepner, Carter and Hess, periodically became sexually mature as females and ours, sub-cultured from their clone, under another set of culture conditions have never become sexually mature as females All factors considered, we believe that the difference between *S grande* and *S. oesophagium* are not sufficient to be of specific caliber. We are therefore rejecting *S oesophagium* as a valid species. A description of *S. grande* follows·

Healthy individuals of one zooid measure about 1.9 mm. The length of single-zooid specimens is highly variable because of the fact that a newly formed individual from an anterior zooid may have a very short, free tail region, whereas, such an animal formed from a posterior zooid will have a long, free tail region. Single zooid individuals are rarely encountered in healthy cultures. Our longest zooid-chains measure as much as 6 0 mm in length.

In reflected light the animal is white except for the enteric region which in well-fed specimens may be orange. In transmitted light the epidermis is faintly yellowish or brownish, the pseudocoel translucent, the pharynx brownish and the enteron, dependent upon its food content, orange to brown with a generally granular appearance.

From above the body has the appearance of a cylinder tapered at both ends In front of the mouth the body tapers rather abruptly. Posteriorly tapering begins somewhat anterior to the caudal end of the enteron and proceeds posteriorly to the narrow, free tail region This free tail region is sometimes equal to 1/4 the body length The posterior half of the ventral body wall is flattened or even concave. This part of the ventral surface is highly adhesive.

The general ciliary coat is uniform—the length of these cilia is about the same as the epidermal thickness. Long, semi-rigid cilia, 2 or 3 times as long as those of the general ciliary coat, are sparsely distributed over the body

The numerous, large, rod-shaped, epidermal rhabdites are disposed perpendicularly or at a slight angle. They may occur singly or in groups. In the slightly contracted state of the epidermis the rhabdite groups become cone-shaped with the apex of the mass inward In the dorsal and lateral regions the distribution of the rhabdites is fairly uniform but on the ventral surface there are three longitudinal tracts free of large rhabdites—a wide median tract, extending from the mouth posteriorly and a narrow tract on each side of this wide median tract.

The ciliated pits are lateral, extremely large and elastic and somewhat wider at their posterior margins.

The nervous system conforms well to the pattern for the genus.

There is a single pair of light-refracting bodies Each body is dish-shaped, composed of many refractive granules or spherules borne on the posterior face of a vesicle closely associated with the posterior ganglionic mass on its respective side. The nervous system and refractive bodies are very similar to those of *S. tenuicaudatum.*

The mouth is extremely large and its most characteristic shape, at rest, is roughly rectangular. The "lips" are mobile and are capable of such enormous stretching that the oral opening may be extended until it considerably exceeds the usual diameter of the body.

The muscular pharynx is long and the posterior portion shows various degrees of folding This is the oesophageal region and there is generally an appreciable constriction between it and the anterior pharyngeal region. The anterior portion is covered externally by unicellular glands—the posterior region is free of glands Histologically the posterior region shows a much thinner wall and its epithelium has a much lighter ciliary coat than that of the anterior region (Nuttycombe and Waters 1935c)

Most of the cells of the enteric epithelium are finely granular and show refractive droplets of various sizes Clear vacuoles are very prominent in starved specimens In addition to these enteric cells are found fairly numerous cells ("gland" cells) which show masses of larger refractive granules The internal margins of the enteric cells are finely ciliated.

The pseudocoel contains a variety of cells as to size, shape and color. The cells of the pseudocoel in the anterior and posterior regions of the body stand out sharply

The radial musculature of the pharyngeal region is fairly well-developed but does not approach the strength of the corresponding musculature in *S virginianum*, *S predatorium* or *S. bicaudatum*. The radial musculature in other parts of the animal is relatively well-developed.

The prominent protonephridial tube passes from beneath the transverse commissure posteriorly over the pharynx and enteron by an undulatory path The ventral nephridiopore varies in its location from about half-way between the end of the enteron and the end of the pseudocoel to almost the posterior tip of the pseudocoel Its usual point of exit is near the middle of the free caudal region

When the male gonad is present it appears as a rather large, lobulated structure located above the anterior pharyngeal region

This species feeds primarily upon large masses of material such as bacterial glea or sediment containing small plants (algae, etc) and small animals (protozoa, rotifers, etc). It cultures easily in wheat-grain infusion but its reproduction is rather slow.

Specific diagnosis 1 pair dish-shaped, light-refracting bodies each composed of many (more than 20) spherules, protonephridiopore near middle of caudal triangle, pharyngeal glands restricted to anterior part of pharynx, 3 tracts on the ventral surface posterior to the mouth free of large rhabdites

S tenuicaudatum v Graff (Pl IV, Fig 1)

Graff, 1911, 1913, Kepner and Cash, 1915, Van Cleave, 1929, Nuttycombe 1932*a*, Van Cleave, 1929, 1934

This species is probably the most widely distributed species of the genus in the United States. It has been reported from the whole Atlantic seaboard and the Midwest We have found it very prevalent in the 5 Southern States (Virginia, North Carolina, South Carolina, Tennessee, and Georgia) in which we have collected Nasonov (1926) and Beklemischev (1917) reported it from Russia It is also probably the easiest of all species to culture in wheat grain infusion

Our type variety of this species has a maximum observed length of 5 0 mm for a chain of 8 zooids The usual number of zooids is 3 to 5 with a length of 1 5 to 2 5 mm. Single underfed zooids may measure as little as 0 3 mm

The body is roughly cylindrical but is somewhat flattened ventrally The anterior end is bluntly rounded, the posterior end tapers gradually from near the posterior end of the enteron to the somewhat pointed caudal tip. The enteron-free caudal region varies in length but is always considerable if the specimen is not newly formed from an anterior zooid. This caudal region is highly adhesive on the ventral side.

In reflected light the color is milky white except for the enteron which may appear somewhat dark In transmitted light the enteric region is yellowish to dark brown and the rest of the body is translucent to brownish

The general epidermal ciliary coat is fine and heavy—the cilia are approximately as long as the epidermal thickness Occasional long, fine, semi-rigid cilia are scattered over the body.

The rhabdites of the epidermal cells are rod-shaped, disposed perpendicularly to the epidermis and may occur singly or in packets.

The ciliated pits are large, dorso-lateral in position and wider at their posterior margins

The nervous system conforms to the pattern of the genus

There is a single pair of dish-shaped light-refracting bodies, each of which is composed of 20-50 granules or spherules covering the posterior face of a vesicle closely associated with an outgrowth from the posterior ganglionic lobe on its respective side

The mouth at rest is crescent-shaped Its "lips" are fairly mobile

The pharynx is rather short and broad The pharyngeal wall contains large bands of longitudinal fibers which are very prominent at the points of convergence around the mouth. Circular fibers are not so prominent The outer pharyngeal wall is covered almost to its posterior end by large unicellular glands The pharyngeal lining is ciliated. The pharyngo-enteric sphincter is located somewhat below the center of the anterior enteric wall

The enteric tube conforms to the body shape in the region in which it lies It ends rather bluntly rounded, somewhat anterior to the posterior part of the pseudocoel leaving an enteron-free caudal region. This caudal region in one variety of the species is seldom more than 1/8 the total body length, whereas, in the others this region is characteristically about 1/3 the entire body length. The enteric lining is ciliated. The cells of the enteric epithelium contain many small granules and vacuoles Occasional cells which contain masses of transparent refractive granules (usually much larger than the scattered granules of the other enteric cells) stand out very prominently except when the enteric contents are dark. The cells containing these granular masses are called, in most descriptions, "gland cells" but we have not been able to find any demonstration of their function. The number of granules in such a mass is variable.

The general parenchyma contains cells of various sizes and shapes. Many of the larger cells are finely granular.

The radial musculature is quite evident in the pharyngeal and caudal regions but is less prominent in the enteric region

The protonephridial tube passes posteriorly from beneath the transverse brain commissure dorsally over the pharynx and enteron Posterior to the end of the enteron it is generally thrown into several loose coils and finally opens ventrally about (or a little anterior) half-way between the posterior enteric tip and the end of the pseudocoel

Reproduction is asexual as a rule In nature, sexually mature females have been collected several times in the fall (October and November) We have a clone which has been cultured continuously for eleven years but no sexually mature individuals have ever appeared in it.

Specific diagnosis: 1 pair dish-shaped, light-refracting bodies each composed of many (more than 20) spherules, protonephridiopore near the middle of a definite enteron-free caudal region, pharynx almost covered by large unicellular glands, rhabdites uniformly distributed on the ventral surface

S taurum Nasonov (Pl II, Fig 1)

Nasonov, 1924; Kepner and Carter, 1931.

Nasonov (1924) described this species from Crimea; Kepner and Carter (1931) described it from the vicinity of the University of Virginia under the name *S. gigerium* and we have collected it in large numbers near Valdosta and Athens, Georgia.

The description which follows is that of Kepner and Carter. "Specimens usually show well advanced fission planes. Such specimens measure about 1 mm in length. The slender body is spindle-shaped, its greatest width being at the level of the posterior end of its anterior third. The body bears a dense uniform coat of small cilia. The oval ciliated pits are dorso-laterally placed. There are no light-refracting bodies. The anterior lobes of the cephalic ganglia are relatively long. The commissure of the cephalic ganglia lies dorsal to the anterior margin of the mouth The relatively large posterior lobes of the cephalic ganglia extend posteriorly by the sides of the pharynx The mouth is short and somewhat fan-shaped The short pharynx is conical. The enteron extends back almost to the posterior end of the body. The anterior region of the enteron is interrupted by the development of a gizzard It is the presence of this organ that has suggested the name for the species The slender protonephridium opens ventrally somewhat nearer the posterior end of the enteron than the tip of the caudal region Many of these animals have been maintained for over a week in a wheat infusion that supported many protozoa. Specimens for in toto mounts have been well fixed in Zenker's fluid "

This species cultures readily in wheat grain infusions Most of the specimens which we collected showed euglenoid organisms in the pseudocoel

Specific diagnosis Light-refracting bodies absent, protonephridiopore not terminal or subterminal, pharynx short and conical, anterior end of enteron equipped with a gizzard

S brevipharyngium Kepner and Carter (Pl II, Fig 2)

Kepner and Carter, 1931, Tseng-Jui Tu, 1934.

The description which follows is that of Kepner and Carter (1931). We have not encountered this species in our collecting.

"Specimens studied were collected from the mud in the overflow from Edgemont Dairy water-basin on the south side of the Observatory Mountain, July 10, 1929." The Observatory Mountain referred to is about two miles southwest of the University of Virginia. Tseng-Jui Tu (1934) records this species from China.

"The many specimens that appeared in our aquarium after the latter had stood in laboratory for five days, all showed at least one fission plane A specimen, with a single obvious fission plane, measures about 0 6 mm. The body is spindle-shaped tapering less abruptly posteriorly than anteriorly. Epidermal cilia are short and uniform in size and distribution. Ciliated pits are minute and hemispherical There are no light-refracting bodies The slender, relatively long mouth is longitudinally disposed This mouth is guarded by lateral lips that present, in the living specimen, definite contours Within each lip there lies a skeletal-like rod which has a texture similar to that of chitin Chitinous material, however, could not be demonstrated The pharynx extends but a little distance beyond the posterior margin of the mouth The enteron is continuous posteriorly almost to the end of the body The contents of the enteron are finely granular, suggesting that this species feeds upon bacteria and naked protozoa. The mesenchyme appears refractive by transmitted light. Little can be made out of the details of the living mesenchyme "

Specific diagnosis Light-refracting bodies are absent, protonephridiopore ventral and subterminal, pharynx extremely short, each lateral lip of mouth with a skeletal rod, ciliated pits minute and hemispherical

S simplex Kepner and Carter (Pl II, Fig 3)

Kepner and Carter, 1931.

The description which follows is that of Kepner and Carter (1931) They collected this species in the vicinity of the University of Virginia. We have not encountered this species in our collecting

"Specimens have not been found that did not possess two or more advanced fission planes. One with three fairly conspicuous fission planes measures about 1 mm in length The cylindrical body tapers gradually posteriorly and rather abruptly at the anterior end so as to be somewhat cigar-shaped Epidermal cilia minute Ciliated pits very small Associated with each posterior lobe of the cephalic ganglia is a simple granule or light refracting body This body measures about 2 μ in diameter It does not have an attending vesicle These simple refractive elements lie opposite the anterior margin of the mouth These simple bodies have suggested the specific name. In total mounts, the transverse commissure of the cephalic ganglia appears almost spherical, the anterior face being somewhat more convex than the posterior one. The short, but elongated mouth is disposed parallel to the axis of the body The pharynx is not conspicuously glandular. The enteron extends to near the posterior limit of the body. The protonephridium is slender and opens at the posterior end This species frequently appears in dense aquarium infusions some days after the material has been collected Specimens were well fixed, for in toto mounts, in Zenker's fluid "

Specific diagnosis · 1 pair of light-refracting bodies each composed of a simple granule, protonephridiopore terminal, pharynx not conspicuously glandular; epidermal cilia minute, ciliated pits very small, no appreciable enteron-free caudal region.

S membranosum Kepner and Carter (Pl. I, Fig. 2)

Kepner and Carter, 1931.

The description which follows is that of Kepner and Carter (1931). We have not encountered this species in our collecting.

"On October 16, 1929, material from the swampy soil below the spring near top of Mountain Elliot, Augusta County, Va., was placed in an aquarium. The next day many specimens of this species appeared beneath the surface of this aquarium Specimens were very well fixed, for in toto mounts, in Zenker's fluid.

"Specimens, lacking obvious fission planes, measure about 0 5 mm in length. Body spindle-shaped, colorless. Rhabdites absent. Epidermal cilia minute. Cilia of ciliated pits conspicuously long. No light refracting bodies. Anterior lobes of cephalic ganglia much larger than the posterior ones as shown by permanently mounted specimens. Mouth, in free swimming specimen, elongated. Pharynx parchment-like or membranous in appearance This feature has suggested the specific name. A conspicuous muscular labial sphincter appears in our permanent in toto mounts. Enteron extends almost to posterior end of body. Protonephridium is very slender, opening at posterior end of body. Only chains of two zooids have been observed."

Specific diagnosis: Light-refracting bodies absent; protonephridiopore terminal; pharynx parchment-like or membranous in appearance, rhabdites apparently absent, prominent cilia associated with ciliated pits.

S. ciliatum Kepner and Carter (Pl. VIII, Fig 1)

Kepner and Carter, 1931.

The description which follows is that of Kepner and Carter (1931) They collected this species in the vicinity of the University of Virginia We have not encountered this species in our collecting.

"Specimens, without obvious fission planes, measure 1 mm. or less. The body is stoutly spindle-shaped tapering posteriorly into a rather slender caudal region. Epidermal cilia small and uniformly distributed Ciliated pits relatively small Associated with each posterior lobe of the cephalic ganglia is a colorless vesicle that contains on its posterior floor one, two or three more or less rod-shaped light refracting bodies. The narrow mouth is transversely disposed The pharynx is wide; has a thin wall and a relatively large lumen Within this lumen numerous long cilia undulate. These large pharyngeal cilia have suggested the specific name. The enteron extends posteriorly to the base of the tapering caudal region of the body This form is much given to ingesting muck. The slender protonephridium opens externally on the ventral surface a short distance posterior to the fundus of the enteron. A culture was established with four wild specimens on March 16, 1929. On May 1, 1929, all of the many stenostoma, that were examined from this culture, resembled the four original ones. Specimens were well fixed, for in toto mounts, in Zenker's fluid. Specimens thus fixed laid down about themselves a mucus-like deposit such as *S. tenuicauda* deposits about itself under adverse conditions."

Specific diagnosis 1 pair light-refracting bodies each composed of 1, 2, or 3 flattened granules, protonephridiopore not terminal, wide, thin-walled pharynx with heavily ciliated inner epithelium, fairly extensive enteron-free caudal region.

S mandibulatum Kepner and Carter (Pl VIII, Fig. 2)

Kepner and Carter, 1931

The description which follows is that of Kepner and Carter (1931). They collected the species in the vicinity of the University of Virginia We have not encountered this species in our collecting

"Individuals without obvious fission planes measure about 0 33 mm in length. The width of the body is relatively somewhat greater than that of other species The epidermal cilia are relatively long and are uniformly distributed The anterior end of the body is abruptly tapered Upon the oblique anterior margins of the body lie the ciliated pits The ciliated pits in this form are more anteriorly directed than in other forms There are no light refracting bodies The mouth is V-shaped Each arm of the V-shaped lip has a refractive tubercle-like body near its anterior end and the diverging lips opened and closed in a manner that suggested that the tubercle-like bodies might have been chitinous mandibles Chitin tests, however, showed no such material present. The mandible-like motion of the lips suggested the species name The enteron extends posteriorly to near the end of the body Only chains of two zooids have been observed This species made its appearance in great numbers in an old, but not foul, infusion, September 9, 1929. Great numbers of them, sexually mature as females, continued to live in this aquarium throughout September. The ovary in this species is relatively large. Specimens were fixed well, for in toto mounts, in Zenker's fluid."

Specific diagnosis: Light-refracting bodies absent; each side of V-shaped mouth with refractive tubercle-like body near its anterior end, ciliated pits large and anteriorly directed.

S. glandulosum Kepner and Carter (Pl. III, Fig 1)

Kepner and Carter, 1931

This species is apparently rather widely distributed We have collected it from Virginia, North Carolina and Georgia.

The body in specimens of several zooids appears threadlike so great is the length in comparison with the diameter Even in an individual showing one or two fission planes the ratio of length to diameter is about 1 to 20 According to Kepner and Carter this species reaches a maximum length of 12 mm and may show as many as 16 zooids.

The body is roughly cylindrical The anterior end, in front of the mouth, is highly mobile and is continually changing shape, extending and retracting At rest the anterior end is bluntly rounded The caudal region tapers gradually and ends bluntly rounded or truncated

The color in reflected light is milky white. In transmitted light the epidermis is translucent and shows many, nearly colorless, refractive masses ("rosette cells"), the enteric region is translucent or grayish and finely granular The enteric wall may show occasional cells bearing masses of refractive granules and occasional clear vacuoles The region anterior to the enteron is faintly brownish

The general ciliary coat is uniform, the cilia are approximately as long as the epidermal thickness

Kepner and Carter (1931) state that this species lacks rod-shaped rhabdites in the epidermis We have observed fairly numerous, small rhabdites in the head region and have found extremely tiny rhabdites scattered over the rest of the body As observed by Kepner and Carter the epidermis contains "rosette-shaped gland cells" Each rosette is composed of 1, 2, 3, or 4 large, clear, refractive vesicles Kepner and Carter found that products from the rosettes had a lethal effect upon the animal's prey These rosettes are relatively scarce in the region anterior to the level of the transverse cerebral commissure.

Kepner and Carter described paired ventral, lateral and dorsal ciliated pits. The ventral and lateral pits are large and prominent but we have not identified the dorsal pits in living specimens unless they be two ciliated grooves on each side of the mid-dorsal line.

The nervous system conforms to the general pattern for the genus. The anterior lobes of the brain are unusually long.

There are no light-refracting bodies associated with the posterior, cerebral lobes but there are, dorsal to the anterior lobes, refractive granules which are generally so arranged that the units above the left, anterior cerebral lobe are paired with corresponding units on the right side Kepner and Carter reported 4 such pairs of granules Whereas, the spacing is usually regular between the bodies, we have found considerable irregularity in the number and exact position of these refractive bodies and we have further found that the individual "bodies" may be composed of 2 granules or spherules.*

The mesio-ventrally placed mouth is, when at rest, roughly crescent-shaped—the powerfully-muscled oral margin is highly mobile and various shapes occur

The pharyngeal wall is highly muscular. The posterior, outer surface of the pharynx is covered by long-necked gland cells the stems of which apparently open into the anterior part of the pharynx The pharyngeal epithelium is heavily ciliated

The outer margin of the enteric tube is, in optical section, somewhat dentate The enteric cells are usually heavily laden with diffusely scattered granules and vacuoles of various sizes Occasional "gland cells" containing masses of granules occur. The enteric lining is finely ciliated. The enteron extends posteriorly almost to the end of the pseudocoel.

The body wall is unusually well-muscled and is subject to frequent waves of contraction.

There are very few free-cells in the pseudocoel in the enteric region but a few very large free-cells may generally be seen in the anterior portion of the pseudocoel. The radial musculature stretching from the body wall to various internal parts is not very well developed.

The prominent protonephridial tube passes from beneath the transverse commissure posteriorly by a tortuous path above the pharynx and enteron Its pore is terminal or subterminal.

Kepner and Carter state that members of this species are scavengers, are sometimes predatory and will not live in the presence of an abundance of algae We have cultured this species with very considerable difficulty in wheat-grain infusions of protozoa but have reared it with great ease when fed on the small variety of *S virginianum.*

Specific diagnosis 4 pairs (typically) of light-refracting bodies associated with the anterior lobes of the cerebral ganglia, protonephridiopore terminal, more than 1 pair ciliated pits, "rosette" bodies in epidermis.

S saliens Kepner and Carter (Pl. V, Fig 2)

Kepner and Carter, 1931.

The following description of *S. saliens* is drawn largely from that of Kepner and Carter (1931) We have added a few descriptive notes from our studies of several specimens of this species collected at Athens, Georgia and Mt. Lake, Virginia. Kepner and Carter collected this species at the University of Virginia.

Specimens without obvious fission planes measure about 0.62 mm. in length The body is spindle-shaped, its greatest width is in the vicinity of the pharynx and mouth. The ventral surface is considerably flattened.

The general ciliary coat is uniform and dense The length of these cilia is somewhat greater than the epidermal thickness. Sparsely distributed over the body are prominent, slender, stiff, very long cilia. These apparently enable the animal to "leap" suddenly Kepner and Carter (1931) observed *Euplotes* collide with the anterior end of *S. saliens* following which the latter would leap after and catch the hypotrich. "It is its ability to leap that has suggested the specific name for this animal."

There are no epidermal rhabdites of the conventional rod-shaped type but the cells contain isolated granules or globules of considerable size These do not appear to be rhabditic in character.

The "brain" is much like that of *S cryptops.*

The ciliated pits are small and hemispherical.

There are no light-refracting bodies

The mouth is elongated and has definitely delimited anterior, posterior and lateral "lips" The anterior "lip" is less muscular and less mobile Heavy muscle bands are very evident in the lateral and posterior "lips" The lateral "lips" are incessantly opening laterally and closing, much as might the mandibles of an arthropod. Only a very small portion of the pharynx lies posterior to the posterior "lip" There are no obvious pharyngeal glands

The enteron extends to near the posterior end of the body The general enteric epithelium is coarsely granular There may also be seen in this epithelium a few "gland cells" containing compact masses of larger granules The free ends of the enteric cells are ciliated.

The protonephridiopore is located ventrally and subterminally.

This species cultures easily in wheat-grain infusions of small protozoa.

Specific diagnosis Light-refracting bodies absent, subterminal protonephridiopore, very little pharyngeal region posterior to caudal oral margin, powerfully muscled lateral and posterior lips, ciliated pits small, hemispherical; sparse coat of prominent, long, semi-rigid cilia

S. predatorium Kepner and Carter (Pl IV, Fig. 3)

Kepner and Carter, 1931; Nuttycombe and Waters, 1935c.

This species has been collected in Virginia, North Carolina and Georgia Plotnikow (1905*b*) describes a *Stenostomum* species from Russia which we believe is *S. predatorium*

Well-fed, single-zooid specimens of *S. predatorium* measure about 1 mm in length. The maximum observed length was

4.5 mm. for a chain of 9 zooids. We have found an extremely small variety of this species at Mt. Lake, Virginia.

The body is roughly a cylinder tapered at both ends. The anterior end tapers less gradually. There are slight constrictions just anterior and posterior to the pharyngeal region.

In reflected light the color is milky white with a slightly darkened enteric region. In transmitted light the animal is translucent except for the enteron which may be almost black in well-fed specimens. The epidermis and region anterior to the enteron have a slightly brownish tinge.

The general ciliary coat is dense and uniform. The length of the cilia is about the same as the epidermal thickness. Semi-rigid cilia about 2.5 times as long as those of the general ciliary coat are rather freely distributed over the body.

No rhabdites have been identified. The epidermal cells in the region anterior to the pharynx contain tiny granules just beneath their surfaces but these have not been definitely identified as rhabdites.

Lying sunken beneath the epidermis are large glands which, according to Kepner and Carter (1931), "discharge a colloidal material that has the power to paralyze other stenostoma." These large depressed glands occur in no other described American species.

The two ciliated pits are of medium size.

The nervous system conforms to the generic pattern.

There are no light-refracting bodies associated with the cerebral ganglia.

The mouth, at rest, appears as a longitudinal slit somewhat wider at its posterior end. The anterior and posterior "lip" regions remain at the level of the body surface, whereas, the lateral "lip" margins are depressed below the body surface. When the mouth is widely opened the lateral regions are elevated and become continuous with the anterior and posterior regions at the level of the body surface. When, the "lips" are thus extended the mouth opening is approximately circular. The oral sphincter associated with the mouth is extremely powerful.

The extremely long pharynx of *S. predatorium* is the most muscular to be found in the American species of the genus. The general intrinsic pharyngeal musculature is well-developed but it is the radial musculature of the pharyngeal region which is most elaborate. Nuttycombe and Waters (1935*c*) have studied this remarkably muscled pharynx in connection with the feeding habits of this and other species Prominent, unicellular glands are located at the anterior and posterior ends of the pharynx but the mid-pharyngeal region is devoid of gland cells We have been unable to find cilia on the pharyngeal epithelium At rest the anterior mouth margin is just posterior to the extreme anterior end of the pharynx so there is a slight preoral pharyngeal region

The finely ciliated enteric epithelium varies in thickness but is usually somewhat thicker than that of the epidermis. The enteric cells, when laden with food, are almost black but in starved specimens this gives place to tan or gray. The enteric epithelium contains numerous, large, highly refractive vacuoles In general the contents of the cells are highly granular The granular inclusions are usually diffusely scattered but occasional granular masses occur Presumably these correspond to such masses in the "gland cells" of the other species even though the granules in *S. predatorium* are much smaller than is usual The enteron extends almost to the posterior end of the pseudocoel leaving little free tail

The free cells of the pseudocoel are not numerous The radial musculature, other than that of the pharyngeal region, is not prominent.

The protonephridial tube passes posteriorly from beneath the transverse commissure of the brain dorsal to the pharynx and enteron. It opens at the posterior end of the body.

The food of this species consists almost entirely of other species of *Stenostomum*. Its feeding habits are unique. *S. predatorium*, by virtue of its powerful oral sphincter and elaborate radial, pharyngeal musculature, is capable of applying its mouth to the surface of the body of an individual of another species, of dilating its pharynx so as to suck in the part of the body to which the mouth is applied and then, by the contraction of the oral sphincter, of pinching off the part sucked into the oral cavity The piece is then passed through the pharynx into the enteron.

We have maintained cultures of *S predatorium* for 3 years by feeding them on *S. tenuicaudatum.* With ample food this species cultures very readily

Specific diagnosis. Light-refracting bodies absent, protonephridiopore terminal, extremely long pharynx with very elaborate radial musculature, glands limited to anterior and posterior ends of pharynx, large epidermal glands which extend inward into the pseudocoel

S. uronephrium Nuttycombe (Pl IV, Fig. 2)

Nuttycombe, 1931.

This species was collected from ponds at several widely separated points in Georgia. It has never been collected elsewhere

Specimens without well-defined fission planes average 0 74 mm. in length, individuals of maximum length average 1 35 mm. The observed range was 0.64 to 1 5 mm in length The body is roughly cylindrical in shape but faintly flattened ventrally. Posteriorly there is a gradual but marked tapering and the slender caudal region ends somewhat bluntly. The extremely long tail, frequently one third and occasionally one half the total length of the body, is characteristic of fully developed specimens. Anterior to the mouth the body tapers sharply and ends bluntly rounded This anterior region is very mobile and is constantly changing shape

In reflected light the animal appears milky white in color. In transmitted light the body is generally translucent except for the enteron which varies from faintly yellowish to light brown dependent upon the food content The granular "gland cells" of the enteric epithelium stand out prominently.

The general ciliary coat of the epidermal epithelium is uniform. The length of these cilia slightly exceeds the thickness of the epidermis and frequently is almost twice that of the epidermal thickness Very long, extremely fine cilia are sparsely distributed over the body but are fairly numerous on the anterior and posterior ends. The small, rod-shaped rhabdites, which are largely confined to the distal ends of the cells, are particularly evident in the epidermis of the caudal region

The cephalic ganglia conform to the general pattern for the genus except for the compactness of the anterior lobes and the unusually deep lateral indentations of the posterior lobes.

The lateral ciliated pits are small and shallow and in many positions of the head are seen with difficulty

A pair of light-refracting bodies lies at about the level of the posterior margin of the mouth These are composed of 2 to 4 flattened or spherical granules applied to the face of a vesicle.

The mouth is medio-ventral in position and is located near the anterior end Its marginal contour is variable even at rest but is usually nearly circular

The highly muscular pharynx is lined with a finely ciliated epithelium. When at rest its lumen is dilated somewhat just posterior to the mouth. Numerous muscle fibers radiate prominently from the outer pharyngeal wall to the body wall The nuclei of these fibers stand out very sharply. Small unicellular glands are sparsely scattered over the outer pharyngeal wall

The pharynx opens immediately into the enteron the lining of which is finely ciliated. Posteriorly the enteron tapers and ends bluntly rounded The enteric cells are apparently not sharply defined, vary in general color depending upon the food, and show large irregularly located vacuoles. The granular "gland cells" stand out very prominently among the enteric cells

The pseudocoel contains free cells of various sizes and shapes

The protonephridium is rather prominent and passes from the extreme anterior end under the commissure and thence along the mid-dorsal line in a slightly irregular path to near the posterior end of the enteron where it bends abruptly to the right and downward (this curvature has been constant in all of 50 healthy specimens examined for it) and passes beyond the posterior end of the enteron lateral to it The tube now bends sharply to the left and extends posteriorly by way of numerous coils Active cilia may be seen within the lumen of the tube in the region of the coils. The tail region, which is highly adhesive on its ventral surface, may be greatly elongated while being used as an anchor but it is only during extreme elongation that the coils are eliminated by stretching. The protonephridiopore is terminal The prominence of the protonephridial tube in the caudal region suggested the specific name

The species cultures readily in wheat-grain infusions of protozoa and small rotifers but rotifers under these conditions appear to make up the bulk of the food Mass cultures have been maintained for 6 years Division occurs in healthy animals about once in 18 to 24 hours In our experience, the species becomes sexually mature as females in stagnant cultures So far no male gonads have been observed

We have isolated some 150 of the eggs but none of these hatched

Specific diagnosis 1 pair of light refracting bodies composed of not more than 4 granules each, terminal or subterminal protonephridial opening, an extremely long enteron-free caudal region in which the protonephridial tube is elaborately coiled

S. arevaloi Gieysztor (Pl III, Fig 2)

Gieysztor, 1931; Nuttycombe, 1932*b*.

Gieysztor (1931) collected and described this species from Spain. We have collected it a number of times from the Piedmont and Coastal Regions of Georgia and from Virginia Healthy specimens without apparent fission planes measure about 0 75 mm. in length by 0.13 mm in diameter (measurement just posterior to pharynx). The minimum observed length was 0.35 mm and the maximum 2 5 mm. This species frequently shows four fission planes and a maximum of seven has been observed in several specimens.

The body is roughly cylindrical in shape but somewhat compressed ventrally Anteriorly there is little change in the diameter and the extreme anterior end is bluntly rounded Posteriorly there is a marked tapering and the caudal region is usually well pointed. A peculiar feature of the caudal region is that its posterior end is bent sharply upward and is not in contact with the substratum as is the more anterior caudal region the ventral surface of which is highly adhesive The formation of this caudal tip is unusual in that it is an outgrowth from the postero-ventral body wall of the anterior zooid and in that it is well developed before separation occurs After separation of the zooids the outgrowth becomes dorsally directed, apparently through a twist in the caudal region.

In reflected light the animal appears milky white In transmitted light the body is generally translucent and colorless or very faintly brownish except for the enteron which is brownish and shows brownish and greenish granular inclusions.

The general ciliary coat is uniform The length of the cilia is slightly greater than the thickness of the epidermis. Long, semi-rigid cilia seem to be rare although occasional cilia of this type have been seen in the caudal region.

Very tiny, short, rod-shaped bodies, located just beneath the surface of the epidermal cells, appear to be minute rhabdites

The epidermis contains numerous clear, highly refractive bodies Each body is typically composed of several vesicles, of various sizes, so arranged as to take a horse-shoe shape The shape, however, is by no means constant and changes with the varying stresses placed on the epidermis. These bodies are much more numerous posterior to the head region.

The ciliated pits are rather large and somewhat anteriorly directed.

The cephalic ganglia conform to the general pattern for the genus Both anterior and posterior lobes are well defined and the mesial portions of the posterior lobes lie over the mouth.

The light-refracting bodies are peculiar. There are three pairs of such bodies in the head region just beneath the epidermis. Each is associated with a clear vesicle The posterior pair is typically composed of two spherules each, apparently fused together, lying above the posterior cephalic lobes at about the level of the mouth. In several instances one of these posterior units has contained three spherules The middle pair, each member a single spherule, lies just anterior to the posterior margin of the ciliated pits above the anterior cephalic lobes. These spherules are about the same size as those involved in the posterior bodies. Slightly in front of the middle pair lies the anterior pair, each a single spherule, about half the size of the spherules of the middle and posterior units Sometimes one of these anterior bodies is displaced so as to lie mesiad or antero-mesiad to the middle body on the same side.

The mouth is mesio-ventral in position and is located near the anterior end beneath the posterior cephalic ganglia

The pharynx is muscular and its lining is ciliated The latero-anterior pharyngeal region lies under the posterior cephalic lobes. The outer pharyngeal wall is covered with glands similar to those of *S tenuicaudatum* Posteriorly the pharynx is sharply constricted and opens through the antero-ventral enteric wall.

The enteric walls follow the outline of the body posteriorly. The enteron ends bluntly rounded some distance anterior to the end of the body. The enteric epithelium is finely ciliated The enteron is variable in color depending upon the food-content but is usually brownish. Almost invariably the enteric region just back of the pharynx shows very dark, fine, granular inclusions which cause this portion to stand out as an extremely dark region The enteric wall contains varying numbers of vacuoles and darker granular masses.

The general mesenchyme is represented by cells of various sizes and shapes. These are rather plentiful in the region anterior to the enteron, not plentiful in the enteric region, and again rather plentiful in the free caudal region. For the most part these mesenchymal cells are fairly large and translucent with frequent minute granular inclusions

Radial muscle fibers are not very prominent but may be seen running from various internal parts to the body wall

The protonephridium is not readily seen in the region anterior to the mouth but appears to pass from beneath the ganglia posteriorly over the pharynx and enteron in a waving path The protonephridial lumen in the pharyngeal region is highly ciliated and frequently contains elonaged masses made up of transparent granules and stringy material At the posterior end of the enteron the tube usually goes into several coils, although it is occasionally almost straight, and passes posteriorly in the free caudal region to open ventrally not farther back than the mid-point between the posterior end of the enteron and the posterior end of the body. Most frequently the pore is just back of the enteron.

The species may be cultured with difficulty in wheat infusions of small rotifers and protozoa It may be easily cultured on the small variety of *S virginianum*

Sexual reproduction has not been observed in cultures although large numbers of individuals have been under observation for ten months. Division may occur as frequently as every 18 hours

Specific diagnosis This species has the following distinctive combination of features 2 pairs of light-refracting bodies dorsal to the anterior cerebral ganglionic lobes and 1 pair dorsal to the posterior ganglionic lobes, protonephridiopore not terminal or subterminal, a dorsally directed caudal outgrowth

S ventronephrium Nuttycombe (Pl. VI, Fig. 1)

Nuttycombe, 1932*b*

This species has been collected in Virginia and from Bulloch County, Georgia

Healthy specimens without apparent fission planes measure about 0 5 mm in length by 0 07 or 0.08 mm in diameter (measurement just posterior to pharynx) The minimum observed length was 0.3 mm. and the maximum 2 mm. Specimens of more than 3 zooids have not been observed.

The body is cylindrical. In most specimens lateral constrictions between the posterior margins of the ciliated pits and the mouth set the head off rather sharply and give to the head region a somewhat spatulate appearance from above. The anterior end is smoothly rounded in outline and is fairly mobile but is not subject to sharp changes in shape during stretching. There is a gradual tapering posteriorly and the body ends rather bluntly The free caudal region is rarely of an appreciable length.

In reflected light the animal is milky white in color. In transmitted light the general coloration varies considerably. The epidermis is usually translucent and colorless but is sometimes yellowish. In the epidermis appear two distinctive features (1) In the cephalic region are found large, rhabdite-like structures, which are frequently grouped into packets, that stand out prominently and give the head a warty appearance. Rhabdites other than those of the cephalic region are not noticeable. (2) In the epidermis back of the cephalic region there are numerous, large, somewhat irregularly-shaped, granular bodies which stand out sharply Similar bodies occur occasionally in the pseudocoel and are rarely inclusions of the enteric wall.

The pharyngeal region is usually brownish and the enteric region varies from faint (not infrequently lighter than the pharyngeal region) to dark brown depending upon the food-content.

The general ciliary coat of the epidermal epithelium is uniform. The length of the cilia is approximately that of the thickness of the epidermis There are long, semi-rigid cilia, 2 to 3 times the length of the general cilia, sparsely scattered over the body but somewhat more plentiful in the anterior and posterior regions.

The cephalic ganglia are two masses and the transverse connective is heavy.

The ciliated pits are large and prominent.

There are no light refracting organs

The mouth is medio-ventral in position and is located near the anterior end Its marginal contour is usually circular when at rest

The highly muscular pharynx is lined by a ciliated epithelium In the pharyngeal wall brownish longitudinal fiber-masses are very prominent. Pharyngeal glands, somewhat irregular in shape, may be seen lying outside the posterior half of the pharyngeal wall These glands may also occur on the anterior half but are less numerous and less obvious here The pharynx undercuts the antero-dorsal enteric region and opens into the antero-ventral wall of the enteron.

The cells of the enteric epithelium are not very distinct in outline and their free ends are finely ciliated The outer margin of the enteric wall is faintly and irregularly dentate. The enteric epithelium is usually at least half again as thick as the epidermal epithelium and when the animal is extended the enteric lumen is, as a rule, small Dark granular masses, isolated granules and vacuoles of various sizes are common in the enteric wall

In the general parenchyma of the enteric region may be seen scattered cells of various sizes and shapes. In the pharyngeal and cephalic regions large spherical cells are rather plentiful.

The protonephridium passes from the extreme anterior end under the cephalic connective and thence over the pharynx to its posterior end where it bends sharply to the left and passes to the ventral surface of the enteron after which it passes caudad, somewhat to the left of the mid-ventral line, by a slightly irregular path. The peculiar position of the tube suggested the specific name The posterior opening of the protonephridium is subterminal. One case in which the protonephridium passed ventrally to the right has been observed but a dorsal tube posterior to the pharynx has never been observed.

This species cultures readily in wheat-grain infusions and large cultures have been maintained for almost 7 years. Asexual reproduction occurs in healthy animals about once in 24 hours. No sexual reproduction has ever occurred in our cultures

Specific diagnosis Light-refracting bodies absent, a protonephridial tube which lies ventral to the enteron posterior to the pharynx, vesicular epidermal bodies.

S virginianum Nuttycombe (Pl. V, Fig 3)

Nuttycombe, 1931, Jones, 1932, Nuttycombe and Waters, 1935*c*.

S virginianum exists in at least three varieties which differ primarily in size Nuttycombe (1931) poorly described *S virginianum* from Giles County, Virginia and Jones (1932) described the large variety as *S carnivorum* from the University of Virginia and Halifax, Nova Scotia. We have collected an intermediate form from Stone Mountain, Georgia, and a large variety used by Jones from several localities in Georgia, Virginia and North Carolina. Van Cleave (1929), we believe, used this large variety under the tentative name *S leucops.* Van Cleave's collections were made at Chicago, Illinois

We have for several years maintained cultures of these varieties and have attempted to find some constant feature for differential diagnosis but no such features have been found

Nuttycombe in his description of *S virginianum* stated that pharyngeal "glands are not apparent but the nuclei of the muscle fibers in the pharyngeal region stand out sharply " Later studies of this species (specimens from the same clone as those from which original description was drawn) have revealed small glands scattered over the whole pharyngeal region with a somewhat greater concentration near the mouth. These glands correspond both as to size and distribution to those described by Jones for *S carnivorum.* Jones' description of the refractive bodies of *S carnivorum* leaves much to be desired He states, "associated with the posterior lobe of each cephalic ganglion is a colorless vesicle of 'eye spot' very much like that which Kepner and Carter described for *S. ciliatum* " According to Kepner and Carter (1931) each refractive body in *S ciliatum* consists of "a colorless vesicle that contains on its posterior floor, one, two or three more or less rod-shaped light refracting bodies." In our large form *S virginianum* all the characteristics conform to Jones' description of *S. carnivorum* except that the refractive mass associated with the vesicle always appears to be composed of a unit (this unit may show some indentations on its edge) which appears rod-shaped only from the side Jones' figure is that of a considerably compressed specimen and in such an animal the side view of the refractive masses would be obtained. In addition to the morphological similarity the feeding habits of *S. carnivorum* and all varieties of *S virginianum* are similar (see latter part of description)

As Nuttycombe's *S virginianum* has priority we are eliminating *S carnivorum* from our list of valid species. A description of *S virginianum* follows·

Single zooids in the small variety are about 0 40 mm. in length, single zooids of the large variety are about 1 0 mm. in length. The maximum observed length for zooid chains in the small variety is slightly over 1.0 mm , in the large variety, 5 0 mm

The body is cylindrical with its greatest diameter in the region of the pharynx Anterior to the mouth the body tapers sharply—the posterior end of the body narrows gradually and ends bluntly rounded The anterior end is extremely mobile and is constantly changing shape.

In reflected light the color is glistening white In transmitted light the body, except for the enteron which varies in color dependent upon its food-content, is translucent.

The general, epidermal, ciliary coat is heavy and of uniform length The cilia are slightly longer than the epidermal thickness. Long (about 3 times the length of the cilia of the general ciliary coat), semi-rigid cilia are sparsely distributed over the body but are more prominent at the anterior and posterior ends of the body and around the oral opening

The numerous, minute, rod-shaped, epidermal rhabdites are disposed perpendicularly to the surface and are largely confined to the distal ends of the cells.

The two, small, hemispherical, ciliated pits are located laterally or lateroventrally.

The nervous system conforms to the general pattern for the genus.

A light refractive body is associated with each posterior ganglionic lobe. At the end of a stem-like outgrowth from the lobe is a very faintly granular vesicle bearing the lens-like (roughly triangular, sometimes with dentate edges) refractive unit The refractive face is directed postero-mesially

The mouth is approximately round in outline when at rest It is highly mobile and distensible

The pharynx when at rest is of fairly uniform diameter throughout Its walls contain a heavy circular and longitudinal musculature The extrinsic, radial musculature of the pharynx is heavy. The pharyngeal opening into the enteron is guarded by a strong sphincter Small unicellular glands are sparsely distributed over the outer surface of the pharynx but are somewhat more numerous at the anterior end The pharyngeal epithelium is very lightly ciliated.

The enteron extends almost to the end of the pseudocoel leaving very little free tail region The outer enteric wall is faintly and irregularly dentate The enteric lumen is finely ciliated The general color of the enteron varies from yellowish to brown in transmitted light The enteric epithelium is finely granular and rather numerous, prominent cells (gland cells) which contain masses of larger refractive granules also occur These cells stand out very sharply in specimens in which the enteron is not laden with food

In the very limited space between the enteron and the body wall may be seen free cells of various sizes and shapes In the region anterior to the enteron large free cells are fairly numerous between the muscle fibers about the pharynx and around and in front of the cerebral ganglia.

The radial musculature supporting the protonephridium and enteron is well-developed.

The very prominent, protonephridial tube passes from beneath the transverse commissure posteriorly above the pharynx and enteron in a slightly undulating path to the posterior end where it opens subterminally

All varieties of this species characteristically move about ventral side up

According to Jones this species (his *S carnivorum*) is primarily predatory upon other smaller species of *Stenostomum* which it ingests but it is incapable of "pinching" off pieces from the body surface of its prey after the manner of *S predatorium* It is certainly true that *S virginianum* is incapable of feeding by the peculiar method of *S predatorium* and it is further true that it frequently ingests whole individuals of other species or smaller individuals of its own kind but we do not consider this predatory feeding upon *Stenostomum* as primary We have maintained pure cultures of this species without difficulty and except for occasional cannibalism the cultures have subsisted on protozoa and rotifers.

Specific diagnosis. 1 pair light-refracting bodies each composed of apparently 1 to 4 units, protonephridiopore subterminal, pharynx relatively long and tubular with small glands distributed over entire surface and with elaborate, radial pharyngeal musculature, little enteron-free caudal region, fairly prominent ciliary coat and long semi-rigid cilia sparsely distributed over body

S pseudoacetabulum Nuttycombe and Waters (Pl. III, Fig 3)

Nuttycombe and Waters, 1935*a*.

This species was collected in large numbers from ponds in Bulloch County, Georgia

Healthy specimens measure from 0.75 to 2.5 mm. in length We have never encountered specimens without a fission plane and large individuals frequently show seven well-defined planes

The head is sharply marked off by a constriction just anterior to the mouth and is somewhat spatulate. Posterior to the head the body is cylindrical and tapers gradually into an attenuated caudal region The posterior end of this region bears a dorsally directed outgrowth very similar to that described for *S arevaloi* In *S pseudoacetabulum* however the outgrowth arises at the new fission plane as a postero-dorsal outgrowth from the anterior zooid. In well-fed individuals the body as a whole is very thick and heavy

In reflected light the animal is white. In transmitted light the integument and anterior region are translucent or pale brownish. The enteric region is gray, brownish or almost black dependent upon food-content. The enteron has many glistening vacuoles.

The general ciliary coat is uniform—cilia about as long as epidermis (epidermis other than that in free caudal region, here it is thinner than elsewhere) is thick Non-vibratile cilia, three or four times as long as those in the general coat, have been observed in the preoral region but not elsewhere.

Rod-shaped rhabdites, vertically disposed and uniformly distributed, lie just beneath the surface of the epidermal cells

The two ciliated pits are of medium size and laterally placed

The cephalic ganglia conform to the general pattern for the genus Light-refracting bodies associated with the ganglia have not been observed

From above the mouth at rest very strongly resembles a trematode acetabulum This feature suggested the specific name. This sucker-like appearance is due to the fact that the "lips" are invaginated so deeply as to involve about the anterior one-third of the pharyngeal wall. This region may be everted rapidly to form a proboscis-like structure

The pharynx is widened posteriorly to form a cap over the anterior end of the enteron. The pharyngeal walls are highly muscular and prominently glandular A sphincter lies between the pharynx and the enteron The pharyngeal lining is ciliated. The radial muscle fibers from the pharyngeal wall to the body are very numerous

The enteron conforms in shape to the body region in which it lies. It terminates considerably anterior to the caudal end of the animal and leaves an enteron-free caudal region The enteric epithelium is approximately twice as thick as that of the epidermis. Its cells are prominently vacuolate and finely ciliated Occasional granular "gland cells" occur.

The free cells of the pseudocoel are of various sizes and shapes.

The protonephridium passes posteriorly from the preganglionic region beneath the transverse commissure of the cephalic ganglia, dorsal to the pharynx and enteron, and empties terminally beneath the dorsal outgrowth at the posterior end of the body

About half the specimens studied were sexually mature as males The testis is located above and slightly to the right side of the pharynx

Specific diagnosis. Light-refracting bodies absent, protonephridiopore terminal; single dorsally directed caudal outgrowth.

S cryptops Nuttycombe and Waters (Pl VI, Fig 2)

Nuttycombe and Waters, 1935*b*

This species has been collected in considerable numbers from ponds in Bulloch County, Georgia.

The maximum observed length for *S. cryptops* is 0.85 mm for a chain of 5 zooids The minimum for a single zooid 0.25 mm The ratio of diameter to length ranges from 1 to 8 to 1 to 15.

In reflected light the animals are white. In transmitted light the epidermis, pseudocoel and pre-enteric region are translucent, the enteron varies in color dependent upon its food-content

The general ciliary coat of the epidermal epithelium is uniform The length of these cilia generally only slightly exceeds the thickness of the epidermis but occasionally the cilia are twice as long as the epidermis is thick. Sparsely scattered over the body are semi-rigid cilia 3 or 4 times as long as those of the general ciliary coat. The epidermal rhabdites are fairly large, rod-shaped and evenly distributed.

The cephalic ganglia conform to the general pattern of the genus but are extremely large and much elongated.

The ciliated pits are dorso-laterally placed, large and much deeper at their posterior ends

There are two pairs of inconspicuous light refracting bodies of the same general type. The inconspicuousness of these bodies suggested the specific name Both pairs have associated with them large, clear vesicles. The anterior pair lies at the posterior tips of the anterior lobes of the cerebral ganglia and the posterior pair lies, at rest, beneath the posterior lobes The refractive mass associated with each of the vesicles of the anterior pair of light refracting bodies is smaller and less dish-shaped than the corresponding mass for the posterior pair of refractive bodies. The refractive masses of both pairs appear to be finely granular at a magnification of 1500 The connections of the anterior bodies have not been determined, the posterior pair appears to be associated with the posterior lobes The posterior pair has a considerable range of lateral movement and may move mesially until they lie very close to each side of the mouth or laterally until they lie outside the lateral margins of the posterior lobes They are shown in this latter position in the figure for this species.

The mouth is medio-ventral in position and is typically a longitudinal slit the posterior margin of which is located about the middle of the pharyngeal region

The pharynx is short, highly muscled and has associated with its posterior end several long-necked glands of unusually large size Smaller glands also occur more anteriorly in the pharyngeal region The pharyngeal lining is ciliated. The pharynx opens posteriorly into the enteron through a strong sphincter muscle.

The antero-dorsal wall of the enteron overhangs the pharynx Posteriorly the enteron tapers and terminates just anterior to the posterior end of the body leaving only a very short, enteron-free caudal region. The enteric epithelium is generally about twice as thick as the epidermis. The free ends of the enteric epithelial cells are finely ciliated. Lying within the epithelium are fairly numerous, granular "gland cells." The usual vacuoles and fine granules are also present.

The free cells of the pseudocoel are few, of various sizes, and are frequently highly refractive. The radial musculature between the body wall and internal parts is not as well developed as is usual in the genus

The protonephridium is a delicate tube which passes from beneath the cerebral commissure posteriorly above the pharynx and enteron by a tortuous path to its subterminal opening

Only asexual reproduction has been observed. This species cultures readily in wheat-grain infusions containing *Chilomonas* and other small protozoans.

Specific diagnosis Two pairs of light-refracting bodies, an anterior pair lying at the posterior end of the anterior lobes of the cerebral ganglia and a posterior pair lying beneath the posterior lobes, protonephridiopore subterminal, mouth typically a slit the posterior margin of which lies beneath the middle of the pharynx, unusually large "brain", very extensive pre-enteric region.

S kepneri n. sp. (Pl VII, Fig 3)

The specific name *kepneri* is given because of the great esteem which the senior author holds for Dr. William A. Kepner of the University of Virginia

This species has been collected from two ponds in the vicinity of Athens, Georgia, and from several localities in the region of Mountain Lake, Virginia

The mid-region of the body is roughly cylindrical The anterior end tapers abruptly and the posterior end narrows less abruptly to a bluntly rounded tip in front of which there is no extensive enteron-free caudal region.

The maximum observed length was 1.75 mm We have never seen specimens of more than 4 zooids.

In reflected light the animal is white. In transmitted light the epidermis and anterior region are pale brown to translucent, the enteric region yellowish to almost black

The uniform general ciliary coat is composed of cilia about as long as the epidermal thickness No long cilia have been observed. The small, rod-shaped, epidermal rhabdites are largely confined to the distal ends of the cells

The cephalic ganglia are similar to those of *S tenuicaudatum*

The two rather large ciliated pits are laterally placed

A pair of conspicuous, spherical light-refracting bodies are associated with the posterior ganglionic lobes Each spherical unit is very closely associated with a mass projecting from beneath the latero-posterior face of the posterior ganglionic lobe The vesicle of the body is to all appearances very closely applied to the projecting mass We have noted in newly separated individuals and in the heads of well-advanced zooids that the refractive unit may be composed of many small granules This fact suggests to us that the granular type of unit may be the more primitive type and the spherical or lens-like units may be derivatives of the granular type

The mouth is medioventrally placed and is almost circular in outline when the "lips" are at rest

The rather short pharynx has a well-muscled wall and a wide lumen. Externally the pharynx is covered by gland cells. Those over its anterior surface are relatively small whereas those over the posterior surface are very large and the bodies of the most caudal of them extend over the enteric wall Posteriorly the pharynx opens into the enteron through an unusually prominent sphincter

The outer enteric wall is irregularly dentate The enteric lumen is wide. The enteric epithelium is about twice as thick as the epidermal epithelium and its cells are ciliated at their free ends. Within the enteric epithelium may be seen fairly numerous "gland cells" containing masses of fine granules The other enteric cells show the usual vacuoles and dispersed granules. The enteron tapers posteriorly somewhat more abruptly than the corresponding body wall and terminates a short distance in front of the bluntly rounded body wall.

The free cells of the pseudocoel are rather numerous and the radial muscle fibers between the body wall and the posterior end of the enteron are large and numerous

The prominent protonephridial tube passes from beneath the cerebral commissure above the pharynx and enteron by a tortuous path to the posterior enteric region. Somewhat anterior to the caudal tip of the enteron it bends abruptly to the right (occasionally to the left) and passes ventrally to open beneath the enteron

This species cultures readily in wheat-grain infusions.

Only asexual reproduction has been observed.

Specific diagnosis 1 pair of light-refracting bodies, each generally a single sphere, a unique feature is a protonephridiopore located beneath the posterior end of the enteron, pharyngeal glands large, ciliated pits large, little enteron-free caudal region.

S. anops n sp. (Pl. VII, Fig 1)

This species was collected from a swamp about 3 miles northeast of Athens, Georgia.

The thin body is cylindrical except for tapering at the anterior and posterior ends, both of which end in a bluntly rounded termination. There is practically no enteron-free caudal region. The region anterior to the mouth is somewhat flattened dorso-ventrally and is extremely mobile Two or more constrictions are more or less constant features in the region between the anterior pharyngeal level and the ciliated pits. These constrictions are not fixed but result from almost constant activity of the musculature of the body wall in this region

The maximum observed length was 1 25 mm. Specimens of more than 4 zooids have not been seen

In reflected light the animal is white. In transmitted light the epidermis and anterior end of the body are translucent to yellowish, the enteron is gray, brown or almost black.

The uniform, general ciliary coat is composed of cilia which are slightly longer than the epidermal thickness. The epidermal rhabdites are extremely small and are located in the distal ends of the cells. The epidermis contains "rosette" gland cells very similar to those of *S. glandulosum.* In *S.*

anops, however, these bodies are less numerous and are not so prominent as in *S. glandulosum* The ventral caudal region of the animal is highly adhesive

The cephalic ganglia conform to the generic pattern and bear a general resemblance to those of *S glandulosum.*

The dorso-lateral ciliated pits are relatively large. Additional pairs of ciliated pits such as described for *S glandulosum* are not obvious.

Magnification of 1500 revealed no trace of light-refracting bodies

The mouth is medio-ventral in position and exhibits a circular outline when adjacent parts are at rest

The wall of the moderately long pharynx contains circular muscle bands of unusual prominence Externally the pharynx is covered by large, long-necked gland cells.

The enteron passes almost to the posterior end of the body and ends bluntly rounded. The enteric epithelium typically contains numerous, prominent "gland cells" loaded with rather large granules As a rule vacuoles are also rather prominent in the enteric epithelium.

The free cells of the pseudocoel are prominent only in the cephalic region

The protonephridium passes from beneath the cerebral commissure posteriorly over the pharynx and enteron to its opening at the terminal tip of the body

This species cultures very readily in wheat-grain infusions

Only asexual reproduction has been observed.

Specific diagnosis. Light-refracting bodies absent; protonephridiopore terminal; "rosette" bodies in epidermis; little enteron-free caudal region.

S tuberculosum n sp. (Pl I, Fig 3)

This species has been collected in large numbers from the lake at Mountain Lake, Virginia and from a pond at Athens, Georgia

The anterior end of the body is triangular from above with a slight constriction just back of the ciliated pits. Posteriorly the body narrows gradually to the caudal end. The ventral surface is greatly flattened or, as is generally the case, appreciably concave At the extreme tip of the cephalic triangle there projects a short tubercle which arises from a slightly broadened base just ventral to the extreme tip of the head We have not been able to notice any marked structural adaptations associated with this tubercle nor have we ascertained any special function except that it seems to be extremely sensitive and may serve as a tactile organ. This tubercle suggested the specific name There is usually a considerable enteron-free caudal region

The maximum observed length was 0.8 mm for a chain of 4 zooids (we have not seen a longer zooid chain than this) and the minimum length for a single zooid 0 2 mm.

In reflected light the animal is white and in transmitted light translucent or faintly yellowish except for the enteron which is yellowish, orange or greenish.

The uniform, dense general ciliary coat is composed of cilia the length of which is 3 to 4 times the epidermal thickness Prominent, long, semi-rigid cilia, some of which are as long as the greatest diameter of the body, are sparsely scattered over the body These long cilia appear much as those of *S. saliens* The distal ends of the epidermal cells bear tiny rhabdites

The cephalic ganglia fit well into the general pattern for the genus.

The two ciliated pits are dorso-lateral in position and are much wider at their posterior margins so that they appear to be directed anteriorly

There are no light-refracting bodies.

The mouth is V-shaped and, viewed from the ventral side of the animal under low magnification, the refractive nature of the "lips" gives the appearance of containing a skeletal material However, actual skeletal elements cannot be found. The powerfully muscled "lips" tend to operate laterally

The ovoid pharynx is short, powerfully muscled and has associated with it very large unicellular glands. The anterior end of the enteron overlies the posterior end of the pharynx, The outer enteric wall is prominently dentate. The enteric epithelium, which is about 4 times as thick as the epidermal epithelium, normally contains a few "gland" cells filled with very fine granules, many vacuoles and numerous fine scattered granules The internal margins of the enteric cells are ciliated. The enteron does not usually extend to the extreme caudal end of the body

The free cells of the pseudocoel are generally small and for the most part are highly granular.

The delicate protonephridial tube passes from beneath the transverse commissure posteriorly over the pharynx and enteron by a somewhat tortuous path and empties terminally

This species feeds on active protozoa and is capable of darting forward with amazing rapidity for the capture of its prey. The rapidity of its movement even exceeds that of *S. saliens* which has the same prominent long cilia and feeding habits

This species may be cultured with great ease in wheat-grain infusions

Specific diagnosis. Light-refracting bodies absent, protonephridiopore terminal; mouth V-shaped, pharynx muscular, short, ovoid with large gland cells, ciliated pits prominent and anteriorly directed, very prominent, long, semi-rigid cilia sparsely scattered over body, a short tubercle projecting from the ventral margin of anterior tip

S pegephilum n sp (Pl. I, Fig. 1)

This species was collected in large numbers from 2 springs in the region of the Mountain Lake Biological Station, Mountain Lake, Virginia. Both of these springs, located at an elevation between 3700 and 3900 feet, are very cool (42° to 46° F.).

The body is typically a cylinder tapered gradually at the posterior end and more abruptly at the anterior end. There is little ventral flattening The general body shape is somewhat more variable than for most species of the genus; some specimens appear rather plump whereas others are quite slender

The anterior end is mobile and is capable of assuming a variety of shapes.

The maximum observed length was 0.9 mm. for 2 zooids (we have not encountered individuals of more than 2 zooids) and the minimum length 0.26 mm.

In reflected light the animal is white. In transmitted light the body, except for the enteron, is translucent, the enteron is yellowish, greenish or gray

The epidermis is unusually thick. The general ciliary coat is uniform and is composed of cilia one and one-half to twice as long as the epidermal thickness. Sparsely scattered over the body are delicate, long cilia about twice as long as those of the general ciliary coat. The extremely tiny rhabdites are confined to the distal ends of the epidermal cells.

The cephalic ganglia are elongate and in general conform to the generic pattern.

The two ciliated pits are medium in size and are latero-ventral in position.

There are no light-refracting bodies.

The mouth is a trasversely disposed ovoid opening

The pharynx is muscular and when extended is oval in shape The posterior pharyngeal wall is frequently thrown into folds so as to give the rear of the pharynx the appearance of a separate chamber The pharyngeal lining is very heavily ciliated. The outer surface of the pharynx is covered by unicellular glands of medium size. Posteriorly the pharynx opens into the enteron through a sphincter.

The enteron rarely extends to the extreme caudal end of the pseudocoel. The outer enteric wall is only faintly and irregularly dentate The enteric epithelium has 2.5 to 3 times the thickness of the epidermis. The enteric lumen is wide. The inner surfaces of the enteric cells are finely ciliated. "Gland cells" containing masses of small granules are fairly numerous in the enteric epithelium.

A very evident feature in the pseudocoel of this species are numerous, highly refractive masses composed of granules of various sizes. There are also in the pseudocoel cells of the usual types

The prominent protonephridial tube follows the conventional path over the pharynx and enteron to its pore at the terminal tip of the body.

This species apparently secretes much mucus and is given to forming cocoon-like structures of sediment particles It is sometimes quite difficult to dislodge specimens from the sedimentary masses The animals show little tendency to rise to the surface in an aquarium and have to be searched for in the sediment on the floor of the vessel

This species does not culture readily in wheat-grain infusions but may be cultured easily in sediment containing protozoa and unicellular algae It apparently feeds upon sediment and algae.

Only asexual reproduction has been observed

Specific diagnosis. Light-refracting bodies absent, protonephridiopore terminal, mouth typically transverse, ovoid, pharynx covered by glands of medium size, ciliated pits medium size, ventro-lateral in position, no special epidermal bodies, rhabdites extremely tiny, usually prominent refractive masses in pseudocoel

Poorly Described Species or Species of Questionable Validity

S leucops Dugès

A. Dugès, 1828, O Schmidt, 1848, Graff, 1882, Ott, 1892, Graff, 1904, Graff, 1913. See Graff 1913 for synonymy of this species, for other papers see abstracts in Bronn's Das Tierreich Turbellaria II. Rhabdocoelida

The most perplexing problem which we have encountered concerns the validity of *S. leucops* as an American species. The literature is replete with references to *S. leucops* For instance, Ott (1892) made an extensive biological study of this species, Child (1901, etc) used it for a study of fission and regulation and later for comparative studies in reconstruction. Kepner and Cash (1915) described the ciliated pits of a species they supposed to be *S. leucops* and Van Cleave (1929) used a species which he tentatively identified as *S. leucops* for studies in fission and reconstitution Van Cleave (1929) states that

Child "now believes his identification of the species he then called *S. leucops* to have been incorrect and that the form was probably *S tenuicauda*" Kepner and Carter (1931) state that they believe Kepner and Cash described the ciliated pits of *S tenuicaudatum* instead of *S. leucops.* Kepner further states that, if the original description of *S. leucops* be correct, he has never found *S. leucops* in Virginia. We are convinced from his description, sketches and discussion of the reconstitutional behavior that Van Cleave (1929) used *S virginianum* instead of *S. leucops*

Ott's lengthy description of the species still leaves the status of *S leucops* very uncertain. He describes light-refracting bodies which might well be those of *S. tenuicaudatum* except for the fact that he does not mention the vesicle. He states that they are connected to the posterior brain lobes by a thin nerve. We are very dubious about any light-refracting body without an associated vesicle, even though *S. simplex* has been so described, particularly if it be of the dish-shaped type Ott described the protonephridiopore as lying sometimes in the middle of the triangular, enteron-free, tail region and sometimes near the end of that region The latter condition, as he points out, would obtain in newly divided anterior zooids. In the "short-tailed" variety of *S. tenuicaudatum* identical conditions are found with reference to the protonephridiopore. Ott's description of the pharynx and other parts of *S. leucops* conforms perfectly to the description of *S tenuicaudatum* He fails to mention the "enteric gland cells" which von Graff (1911) figures so prominently in his *S tenuicaudatum* but we have seen *S. tenuicaudatum* without these Indeed we feel almost certain that *S. leucops* according to Ott is the same as von Graff's *S. tenuicaudatum.*

Von Graff (1913) gave a description of *S. leucops* which appears to us, after studying the sources, to be a composite from the descriptions from Ott, Child and others. Child, as has been previously stated, now believes he used *S. tenuicaudatum* instead of *S. leucops* and it has been shown above that there is little of Ott's description which cannot be applied to *S. tenuicaudatum* Von Graff (1913), in his description, suggests two features which surely do not fit *S tenuicaudatum* According to him the pharynx of *S leucops* is not uniform in structure but has a sort of oesophageal portion Further, he describes a rhabdite-free tract down the middle of the ventral surface. Both of these features are found in *S. grande* The opening of the nephridiopore, according to Ott, is located near the end of, or in the middle of, the tail "triangle." According to von Graff the opening is terminal or subterminal We interpret terminal to mean extreme tip and subterminal to mean just anterior to the tip We do not interpret "subterminal" as corresponding to "in the middle of the tail triangle" In short, there is no agreement as to specific characteristics for *S leucops* It seems evident that some variety of *S. tenuicaudatum* has been used in the United States for *S. leucops* Furthermore, von Graff's description, which is the most extensive except for Ott's, seems to be a useless composite involving features drawn from several sources of questionable validity

It might seem reasonable to reject the name *S tenuicaudatum* and accept the name *S leucops* as the valid specific name except for the all-important fact that von Graff's original brief description (1911) of *S tenuicaudatum* fits the species which we are using under that name and Ott's extensive description of his *S leucops*, with the exception of his questionable interpretation of the light-refracting bodies, also fits *S tenuicaudatum.* Von Graff (1911), without descriptive text except for a comment on the length of zooids and rhabdites, records the collection of *S leucops* at Rochester and Ontario. This and other collection records are open to the same criticism as those given Ott's *S leucops.*

We are therefore placing this species in our second list as a highly questionable species. Indeed it seems likely to us that the descriptions of *S. leucops* are so unreliable as to invalidate completely that species in any fauna, we rather strongly suspect that it is a synonym for *Stenostomum.*

S agile Silliman

Silliman, 1885, Graff, 1911, Graff, 1913

Silliman collected this species in Monroe County, New York, von Graff states that it is abundant in the environs of Rochester, New York, and that he also found it in Switzerland and Bohemia It has been reported from Europe by Fuhrmann (1894), Meixner (1915), Nasonov (1926), and others and by Okugawa (1930) from Japan

We, with considerable misgiving, have placed *S agile* in this group of questionable species We have carefully studied and compared the original description by Silliman (1885) and those of von Graff (1911, 1913) The most significant specific feature appears to us to be the light-refracting body This feature, as we have shown, is extremely constant within rather narrow limits and is reliable as a specific character The light-refracting body in *S agile* is unique in the American species if it is as described by von Graff. The original and von Graff's descriptions differ in several points Silliman (1885) describes the light-refracting body as a sac which bears in its posterior part a strong light-refracting body which appears homogeneous His figure shows an elevation on the anterior, concave face of this refractive unit. According to von Graff (1911) the body is composed of a fluid-filled vesicle which bears on its posterior face a lens-like refractive unit (4 microns in diameter) which sometimes shows striations or wrinkles Lying embedded in a pit in the anterior face of this refractive lens is a globule. Von Graff (1913) omits any reference to the striae or wrinkles of the refractive unit but again describes the globule lying in a centrally located depression in the anterior face of the refractive lens. A refractive body with a globule lying in the anterior face of its refractive unit would unquestionably establish this as a valid species

Silliman describes pharyngeal glands as being confined to the posterior end of the pharynx, whereas von Graff (1911, 1913) described and figured the glands over the entire pharynx

Silliman described the ciliated pits as supplied by nerves from the anterior ganglionic lobes but Graff (1911) stresses the fact that the pits lie embedded in the anterior ganglia.

The three descriptions, Silliman (1885), von Graff (1911, 1913) agree in most other features. A composite of these follows.

Solitary zooids measure about 0 75 mm. in length, 5-zooid chains about 4 mm Both ends of the body are tapered but blunt The extensive anterior end contains elaborate transverse "muscle plates" The animal is colorless or occasionally gray or yellowish There is a well-developed, epidermal, ciliary coat The rhabdites are 2–4 microns in length The posterior end of the body bears adhesive cells which allow firm attachment The brain conforms to the generic pattern. The ciliated pits are far anterior and extra long cilia are associated with them The light-refracting bodies have been previously described The mouth lies in the anterior 1/5 of the body The pharynx is long and covered by glands (see previous discussion of this feature) The intestinal epithelium is ciliated and contains glistening oil droplets and yellowish-green granules. The excretory system is similar to that of the generic pattern The protonephridiopore lies somewhat anterior to the posterior end The pseudocoel contains nucleate cells Silliman figures and describes a saccular testis above the anterior pharyngeal region

S incaudatum Sonneborn

Sonneborn, 1930 *a* and *b*.

Sonneborn originally isolated a single specimen of this species from a culture in the Zoological Laboratories at Johns Hopkins University. The exact source of the culture could not be ascertained

We think it very probable that this is a valid species but because of the nature of the description we are not placing it with our list of valid species. Sonneborn states that members of this genus have "one or more pairs of light-refractive organs of supposed optic function" and then fails to mention even the presence or absence of such organs in his description of *S. incaudatum.* His figures are of little value in determining the validity of his species.

His description is reproduced here

"*Stenostomum incaudatum* differs from all other species of the genus in its combination of two characteristics, the absence of a tail, and a particular form and structure of the pharynx. The posterior end of the body tapers but slightly and ends bluntly; the pharynx lacks glands, is short, and is nearly as wide as the head. A full description follows.

"The body forms a flattened cylinder of nearly uniform depth and width except near the anterior and posterior ends. The ratio of width to length is about one to twenty in the longest chains, about one to five or six in solitary animals. The ratio of width to depth is about seven to five. Chains of as many as nine zooids occur. Single animals may be as long as 0 3 mm ; chains of nine zooids attain a length of 2 0 mm

"In reflected light the whole organism appears white. In transmitted light the head is gray, the trunk dark. The darkness of the trunk is due chiefly to the food within the lumen of the intestine and within the intestinal cells, but even starved specimens have a yellowish brown intestine. Numerous dark green bodies (glands) are applied closely to the outer surface of the intestine, these can be seen more clearly in starved specimens.

"The form and structure of the head are represented in figure 3. In the most anterior part are two groups of transverse muscles Just posterior to these lie the pair of shallow ciliated pits, at the base of each is a ganglion. These ganglia are immediately anterior to a pair of large, trapezoidal cerebral ganglia No commissure between the cerebral ganglia has been observed, but these lie very close together. The most posterior part of the head is fully occupied by a thick-walled, muscular, but non-glandular, pharynx A medioventral V-shaped mouth opens into the pharynx and the pharynx opens through a narrow sphincter into the intestine. The cavity of the pharynx is flask-shaped, with a narrow neck of the flask leading from the mouth to the wide base of the flask near the intestine. The base of the flask is partly occupied by a pyramidal mass of cells with the sphincter in the center. After a food organism is captured, it is whirled around in the pharyngeal cavity for a short time and then pushed back into the intestine through the sphincter.

"The postpharyngeal region presents few unusual features The pseudocoel is very narrow Dark green glands, filled with granules or vacuoles, lie closely applied to the outer surface of the intestine. The distal parts of the intestinal cells are clear and translucent, sometimes containing translucent globules; the proximal parts are dark The ciliated lumen of the intestine is wide. The excretory, or protonephridial, duct has the usual form and position. The ciliated integument is thin and translucent

"No tail is present, the intestine extends to the posterior tip of the trunk"

He cultured this species easily on *Colpidium striatum.*

Species of Very Doubtful Validity

S giganteum Higley

Higley, 1918.

Higley described this species from Illinois

We have no apology to offer in classing this species as questionable. Both the description and the figure accompanying it are too inadequate to be worth anything. The whole description suggests one which might be offered for any of the larger species in a very unhealthy condition. Neither light-refracting bodies nor pharyngeal glands are mentioned and, indeed, the six pages devoted to the description of this species give little idea of its morphology other than its size and shape.

S glandiferum Higley

Higley, 1918.

Higley collected this species in Illinois

The description of this species is somewhat better than that of *S. giganteum* but is wholly inadequate to establish the species. We see some similarity between this species and

S. virginianum but we do not feel that the resemblance is sufficient to jeopardize the position of *S. virginianum.*

S. speciosum Stringer

Stringer, 1918 in Ward and Whipple's Fresh-water Biology, 1918.

The only descriptive material we have been able to locate on this species is found in Ward and Whipple, "Fresh-water Biology," 1918 The specimen figured is sexually mature as a female and the description is so brief as to be absolutely worthless

Described from Nebraska

NOTES ON DISTRIBUTION, COLLECTION, CULTURE, AND REPRODUCTION

There is little space in a paper of this length for discussion of the general biology of the genus We have therefore limited this section to a few very brief notes on distribution, collection, culture methods, and reproduction

Species of this genus appear to be widely distributed. The literature of the American species shows collection records from practically all parts of the country east of the Mississippi Our own collection records show the genus plentiful in New York, Pennsylvania, Virginia, North and South Carolina, Tennessee, and Georgia Foreign collection records (those for the American species are listed elsewhere in this paper) report the genus from all parts of the world.

We have found a variety of species at an elevation of about 5000 feet and an even greater variety at an elevation only a few feet above sea level. Our collection records indicate that *S tenuicaudatum* and *S virginianum* have the widest distribution and are found in greater numbers than other species. *S. grande, S. predatorium, S. saliens, S arevaloi*, and *S glandulosum* are also very widely distributed *S. uronephrium, S. ventronephrium, S pseudoacetabulum, S cryptops* and others have only been collected in restricted territories

Stenostomum are easily obtained from springs, ponds, lakes, slowly running streams or swamps by simply collecting a thin layer (about 1/2 inch) from the floor of the water bed or by collecting sediment-covered aquatic vegetation. We have made satisfactory collections at the very edge where the water was scarcely an inch deep and at a depth of several feet As a rule winter collections are more satisfactory at the deeper levels.

We usually place each batch of collected material in a small aquarium filled with water from the source of the collection Within a few days the culture becomes somewhat stagnant and the *Stenostomum* rise to the surface where they may be easily isolated with a pipette If the site of collection was well selected such a culture will usually yield numerous individuals of from 3 to 5 species

Most species may be maintained in pure culture in wheat-grain infusions Such infusions are prepared as follows Place seed wheat in cool spring water, heat to a boil and allow to cool Add 4 grains of this wheat to 250 cc. of spring water (previously boiled, cooled and aerated) in a culture dish and allow to stand for three or four days—long enough for bacterial growth to get well started—and then inoculate with *Stenostomum*, protozoa, etc from the collection We have maintained a clone of *S tenuicaudatum*, by subculturing it about every six weeks, in such infusions for 11 years Some species, however, do not culture readily by this method. We have found that *S arevaloi*, *S. glandulosum* and *S. predatorium* require other species of *Stenostomum* as food. We have been unable to culture satisfactorily *S bicaudatum* We have included with the specific descriptions notes on culture.

Reproduction is generally by fission and in most species is fairly rapid. We have had as many as 3 asexual generations in 24 hours from the small variety of *S virginianum* and for the same variety we have had a specimen live three weeks without food during which time it did not divide and progressively became smaller The larger species usually divide more slowly than the smaller species Child (1902*a*) described rather thoroughly the morphological changes associated with the process of fission.

Sexual reproduction has not been observed for all species. Sexuality generally occurs intermittently and, as has been pointed out by Sekera (1903*b*), Kepner, Carter and Hess (1933) and others, is apparently dependent upon environmental factors. In nature we have collected *S. tenuicaudatum* sexually mature as females in the fall of the year and Child (1901) and others have reported sexuality in specimens collected at that time of year. Kepner, Carter and Hess report the collection of *S oesophagium* (variety of *S grande*) sexually mature as males during the last week of August and during September but not during other months. They maintained cultures of *S. oesophagium* always sexually mature as males and intermittently as females. We have maintained cultures of this species (*S grande*) for 4 years always sexually mature as males but no female gonads have appeared. On the other hand, we have maintained *S. tenuicaudatum* in wheat-grain infusions for 11 years without the appearance of any sexuality during which time more than 1000 asexual generations have passed

The single, lobulated testis lies in the antero-dorsal pharyngeal region and opens dorsally by a pore. The ova are formed and supposedly undergo their early development in the pseudocoel. There are no ducts associated with the female gonads Keller (1894), Sabussow (1897), Sekera (1903*b*, 1906), Kepner, Carter and Hess (1933), and others have contributed most of the information concerning sexual reproduction in *Stenostomum*. Probably the best discussion of sexuality in *Stenostomum* is that of Kepner, Carter and Hess on sexuality in *S oesophagium*

For general information on the genus we would recommend such papers as those of Graff (1882), Graff in Bronn's Klassen und Ordnungen des Tierreichs (1904–1908) and the later abstract numbers of Bronn's, Graff (1913) and Bresslau (1933). We believe our bibliographic files are fairly complete on this genus up to the present date and we will be glad to supply any special information from these files to those who may desire it

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LABEL ABBREVIATIONS FOR PLATES

cg,	cerebral ganglion
co,	caudal outgrowth
cp,	ciliated pits
do,	dorsal caudal outgrowth
e,	posterior division of pharynx
ec,	epidermic cross-section
en,	enteron
ep,	surface view of epidermis
ep$_1$,	surface of ventral epidermis
ep$_2$,	surface of dorsal epidermis
es,	epidermal body
ese,	epidermal gland
ev,	enteric vacuole
f,	free cells of pseudocoel
g,	intestinal gland cell
gg,	gland of grasping organ
gz,	gizzard
go,	tentacle-bearing "grasping organ" of pharynx
l,	lip
lc,	long cilia
m,	mouth
md,	mandible-like lip
o,	ovary
ph,	pharynx
ph g,	pharyngeal glands
pn,	protonephridium
r,	radial muscle fiber
rb,	light refracting body
s,	ventral view of epidermis showing rhabdite free tracts
t,	testis
tb,	cephalic tubercle
v,	vesicle of light refracting body
vo,	ventral caudal outgrowth

PLATE I

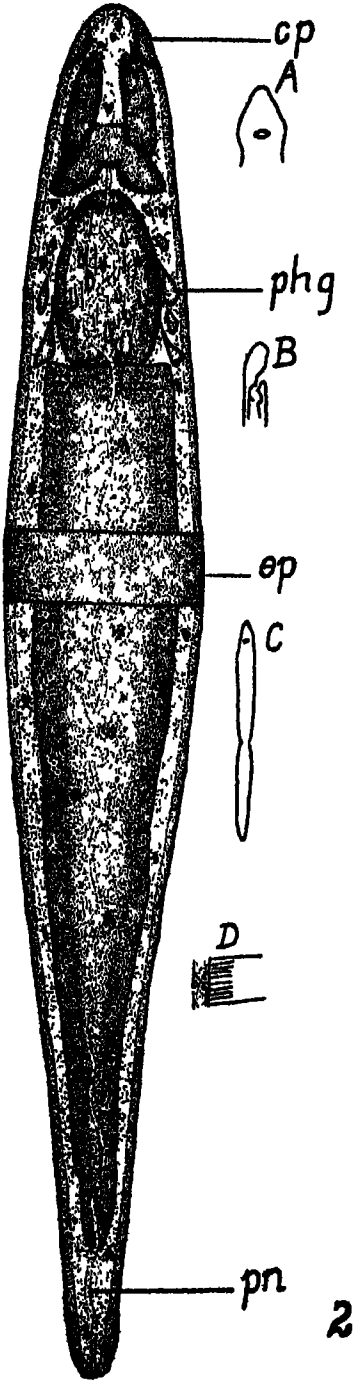
FIG 1 Dorsal view of *Stenostomum pegephilum* *A*, outline of anterior end to show a characteristic shape assumed, *B*, outline of median dorso-ventral section of anterior end, *C*, chain of 2 zooids, *D*, section of epidermis to show rhabdites, general ciliary coat and large semi-rigid cilia

FIG 2 * Ventral view of *Stenostomum membranosum*

FIG 3 Ventral view of *Stenostomum tuberculosum* *A*, chain of 4 zooids numbered to indicate relative age of fission planes, *B*, trans-section through mid region to show ventral concavity, *C*, outline lateral view of anterior end to show position of tubercle

* Redrawn from Kepner and Carter (1931)

PLATE I



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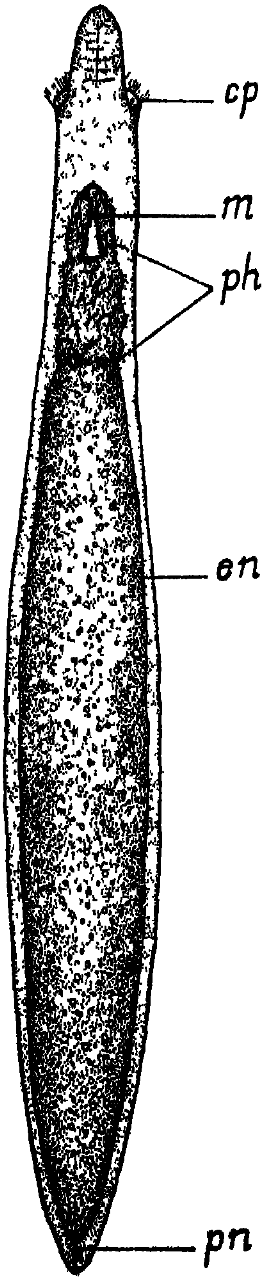

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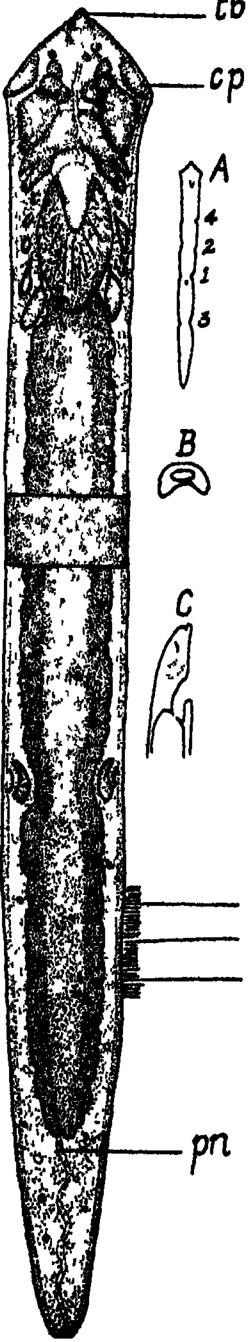

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PLATE II

FIG 1 * Dorsal view of *Stenostomum tauricum*
FIG 2 * Ventral view of *Stenostomum brevipharyngium*
FIG 3 * Dorsal view of *Stenostomum simplex*

* Redrawn from Kepner and Carter (1931)

PLATE II

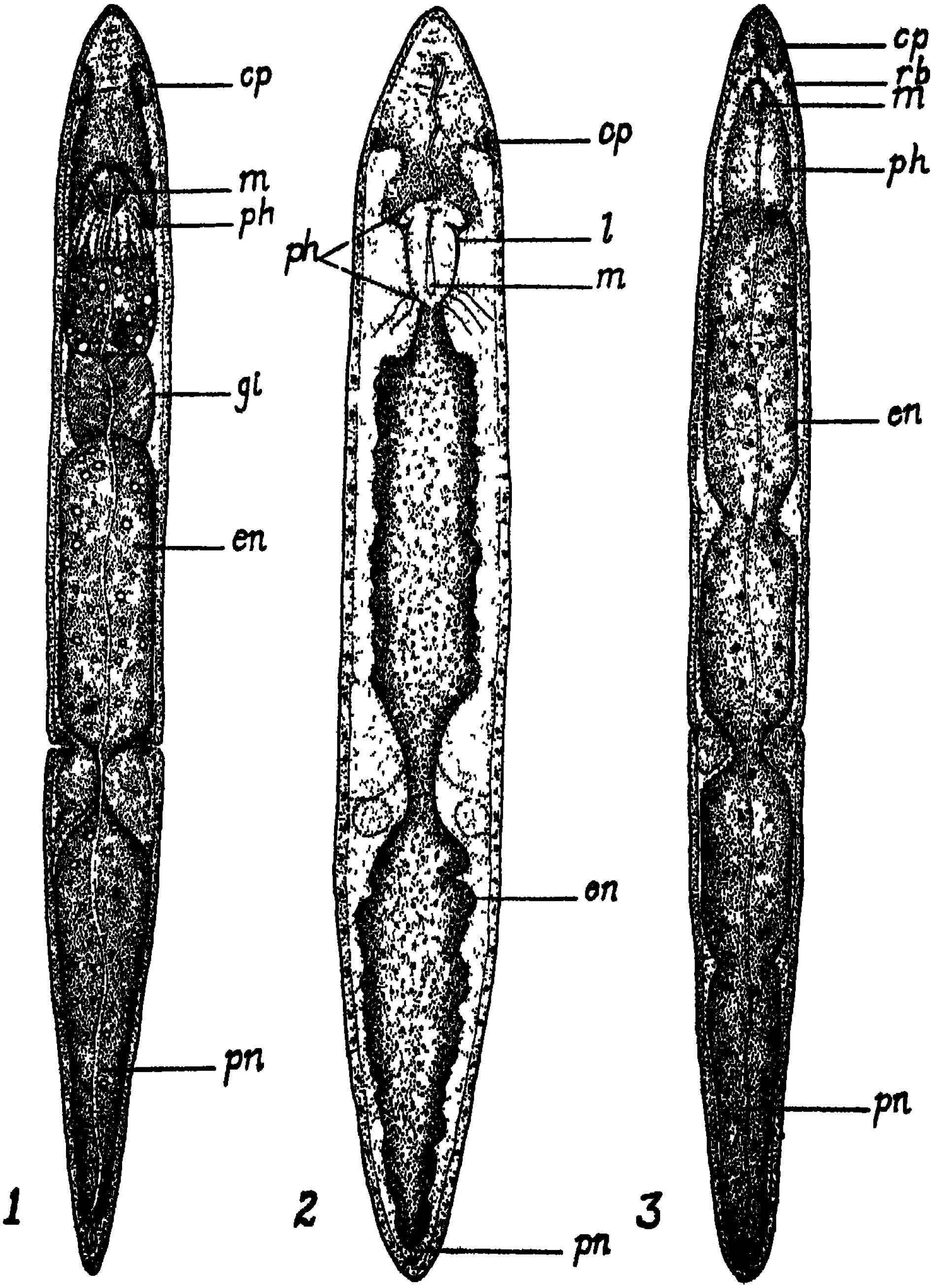


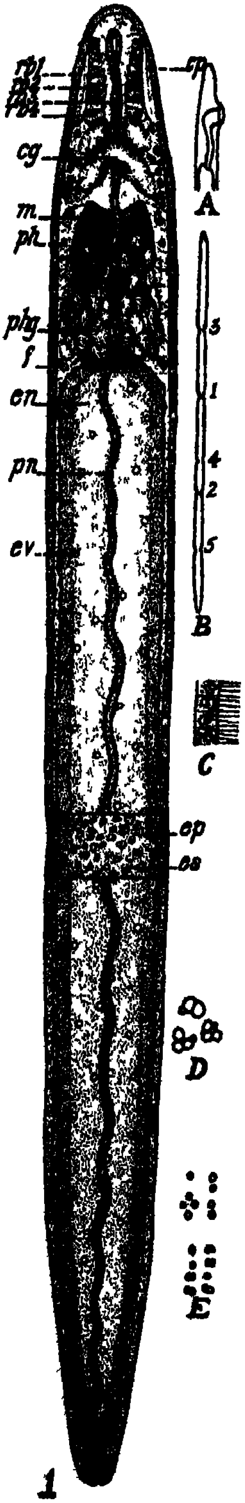
PLATE III

FIG 1 Dorsal view of *Stenostomum glandulosum* *A*, lateral view of anterior region showing shape of pharynx, *B*, chain of six zooids with numbers indicating relative age of fission planes, *C*, section through epidermis showing rosette-shaped gland cells and general ciliary coat, *D*, rosette-shaped gland cells, *E*, two unusual patterns of light refracting bodies

FIG 2 Dorsal view of *Stenostomum arevaloi* *A*, lateral view to show position of developing caudal outgrowth at new fission plane, *B*, ventral view of developing caudal outgrowth at new fission plane, *C*, highly magnified enteric epithelium just back of pharynx to show heavy granules (cilia not shown), *D*, chain of eight zooids with numbers indicating relative age of fission planes, *E*, protonephridium with translucent inclusion, *F*, highly magnified epidermis showing rhabdites, epidermal body and general ciliary coat, *G*, highly magnified enteric epithelium from region about middle of animal (cilia not shown), *H*, unusual pattern of light refracting bodies, *J*, outline shape of epidermal body

FIG 3 Dorsal view of *Stenostomum pseudoacetabulum* *B*, lateral, optical view of anterior end of animal to show protruded "lips", *C*, lateral, optical view of anterior end of animal to show "lips" folded into oral cavity, *D*, lateral, optical view of fission plane showing formation of caudal outgrowth, mouth and pharyngeal region, *E*, section showing enteric epithelium, pseudocoel, radial musculature, epidermis with rhabdites and general ciliary coat, *F*, chain of eight zooids with numbers indicating relative age of fission planes, *G*, posterior end of animal showing caudal outgrowth and opening of protonephridium

PLATE III



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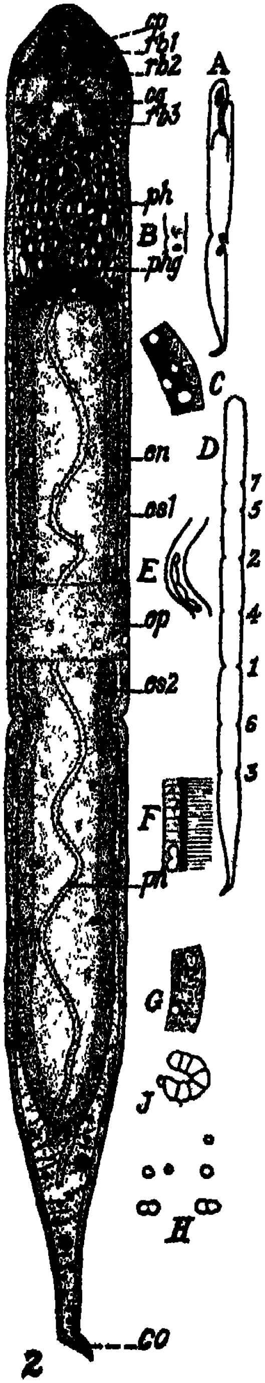

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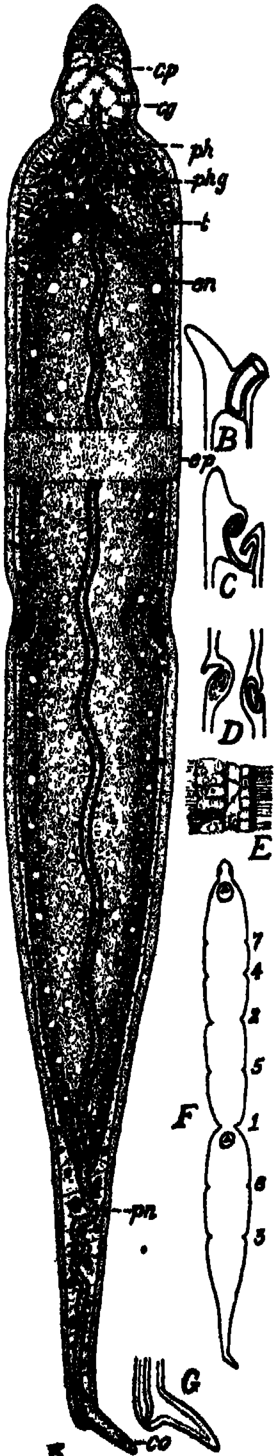

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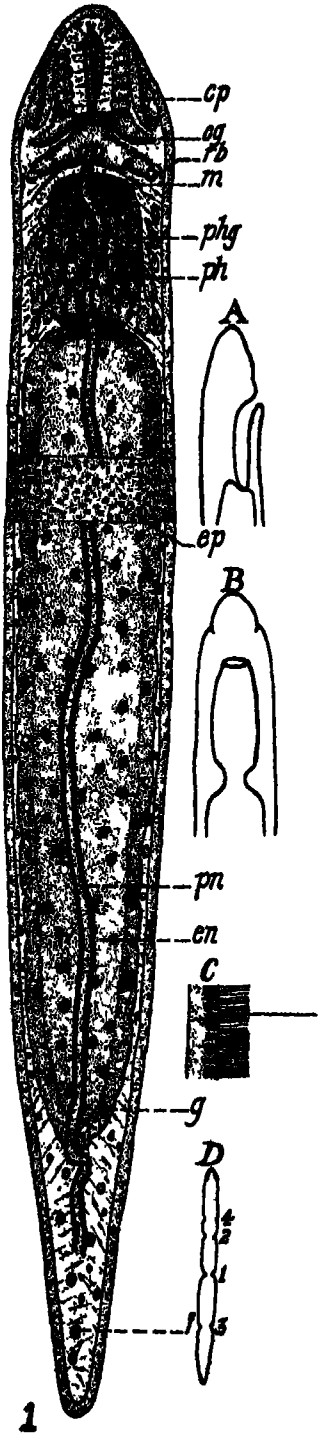
PLATE IV

FIG 1 Dorsal view of *Stenostomum tenuicaudatum* A and B, lateral and dorsal aspects of anterior region to show pharyngeal shape and relationships, C, section through epidermis showing rhabdites, general ciliary coat and a long semi-rigid cilium, D, chain of five zooids, with numbers indicating relative age of fission planes

FIG 2 Dorsal view of *Stenostomum uronephrium* A, varieties of light refractive bodies

FIG 3 Dorsal view of *Stenostomum predatorium* A, chain of nine zooids with numbers indicating relative age of fission planes, B, optical sagittal section of anterior end showing mouth and slight preoral pharyngeal region, C, outline of mouth at rest and open, D, epidermis showing general ciliary coat and semi-rigid cilia

PLATE IV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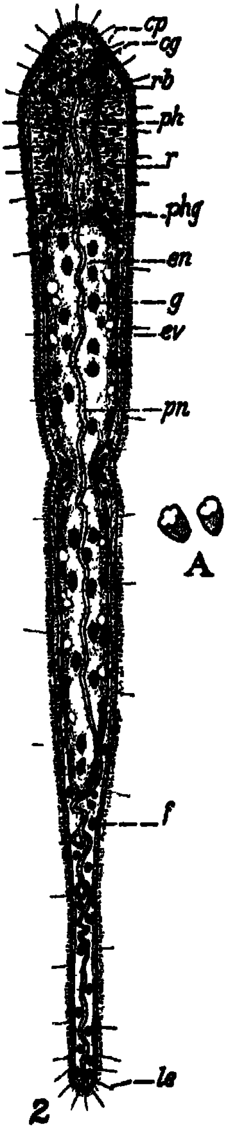
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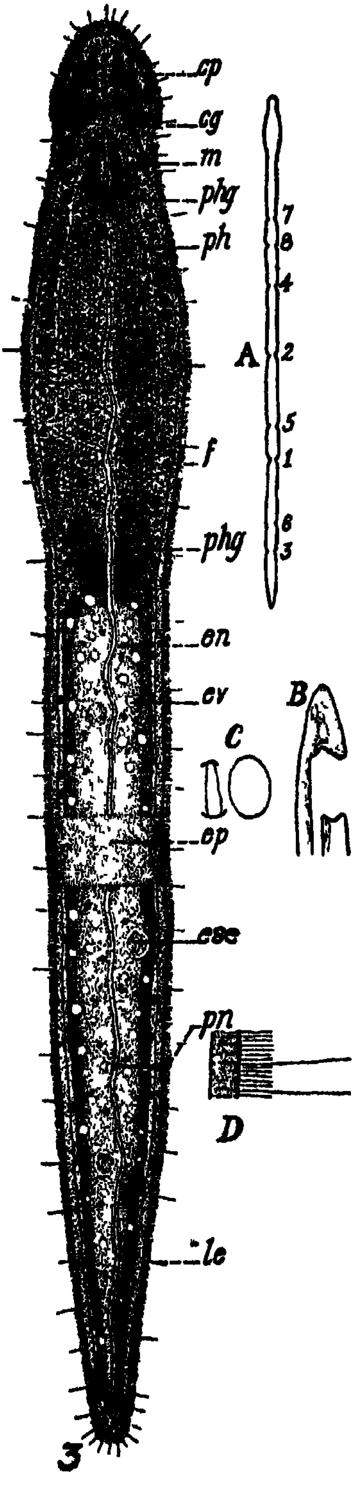
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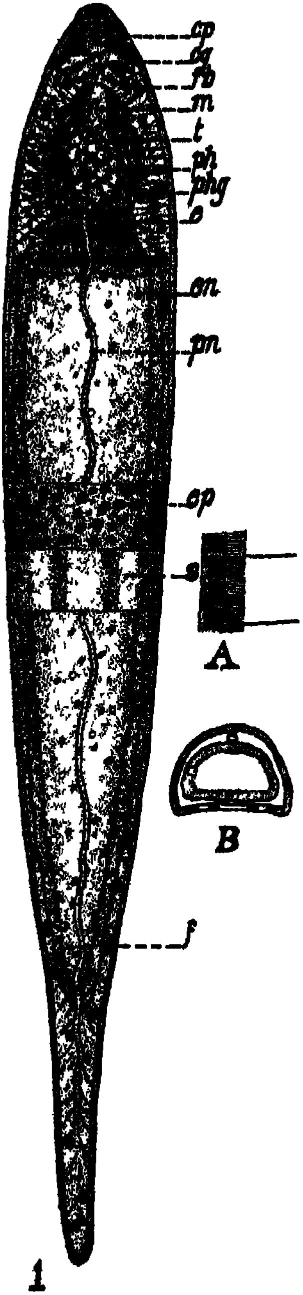
PLATE V

FIG 1 Dorsal view of *Stenostomum grande* *A*, section of epidermis showing rhabdites, general ciliary coat and semi-rigid cilia, *B*, schematic cross section through animal showing epidermis with ventral rhabdite free tracts

FIG 2 Ventral view of *Stenostomum saliens* *A*, diagram showing extremely long, stiff cilia, *B*, section through epidermis showing general ciliary coat

FIG 3 Dorsal view of *Stenostomum virginianum* *A*, lateral view of anterior end showing mouth and pharynx, *B*, ventral view of anterior end, *C*, section showing enteric epithelium (cilia not shown), epidermis with rhabdites, general ciliary coat and long semi-rigid cilia, *D*, varieties of light refracting bodies, *E*, chain of eight zooids with numbers indicating relative age of fission planes.

PLATE V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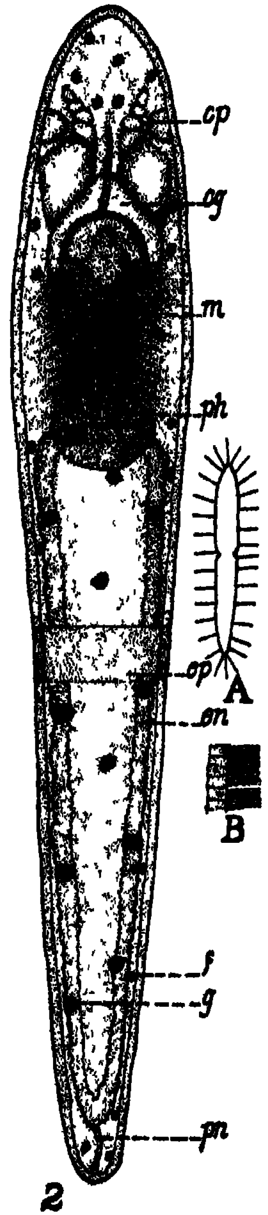
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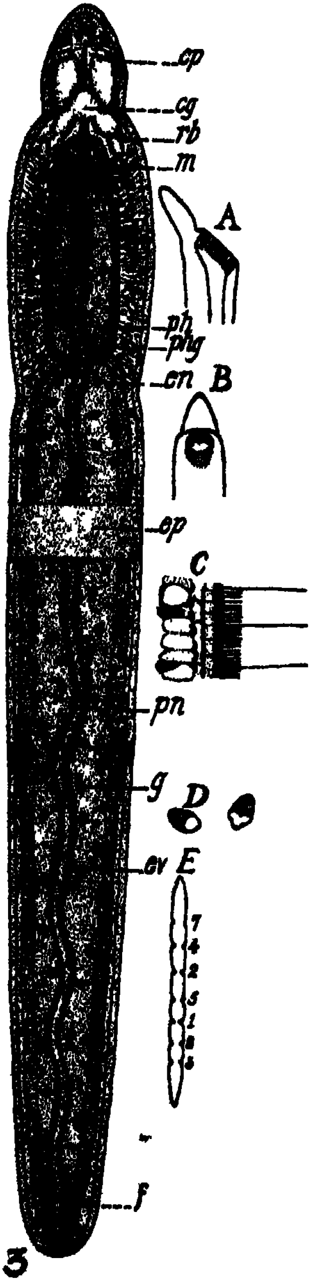
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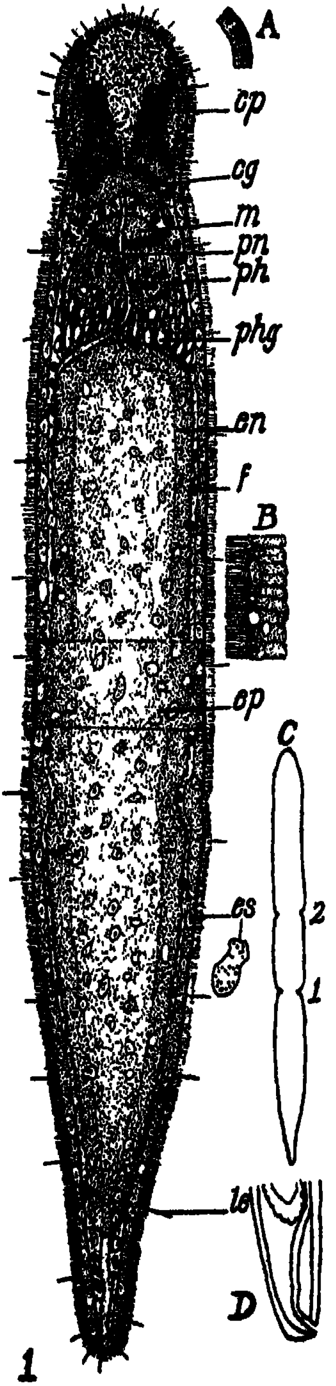
PLATE VI

FIG 1 Dorsal view of *Stenostomum ventronephrium* *A*, section of epidermis at anterior end showing large rhabdites, *B*, section of enteric epithelium, *C*, chain of three zooids with numbers indicating relative age of fission planes, *D*, optical, sagittal section through posterior end showing protonephridiopore

FIG 2 Dorsal view of *Stenostomum cryptops* *A*, optical sagittal section through anterior end showing mouth, pharynx, pharyngo-enteric sphincter and enteron, *B*, chain of four zooids with numbers indicating relative age of fission planes, *C*, section showing enteric epithelium (cilia not shown), pseudocoel, radial musculature, epidermis with rhabdites, general ciliary coat and long semi-rigid cilia

PLATE VI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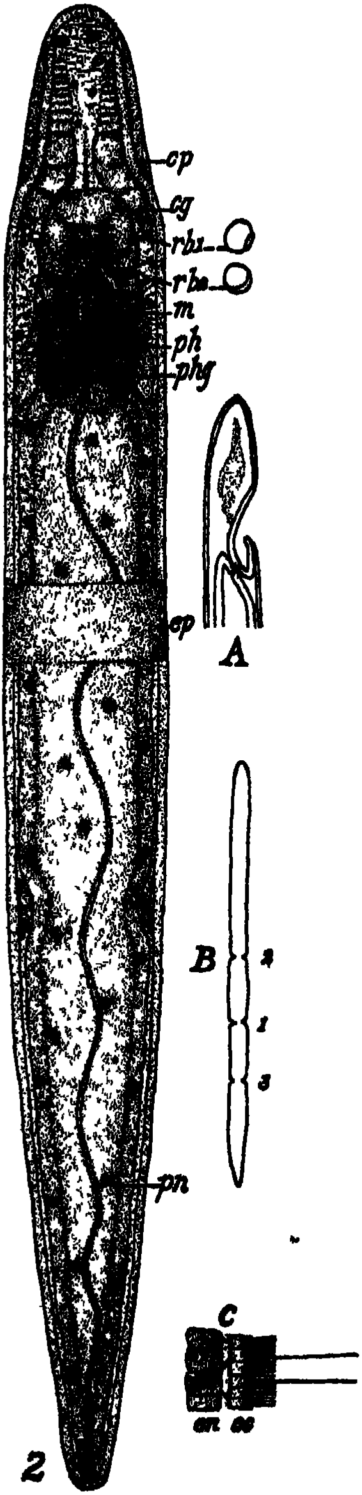
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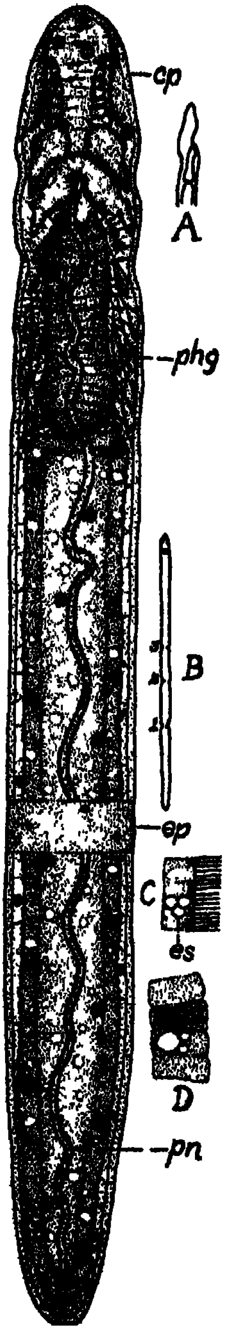
PLATE VII

FIG 1 Dorsal view of *Stenostomum anops* *A*, optical section, in outline, of anterior end, *B*, chain of 4 zooids numbered to indicate relative age of fission planes, *C*, enlarged section of epidermis to show "rosette" body, rhabdites and cilia, *D*, enlarged enteric cells (cilia not shown)

FIG 2 Ventral view of *Stenostomum bicaudatum* *A*, outline of brain from dorsal side to show light refracting bodies of right side, *B*, outline of two-zooid specimen from side to show development of ventral caudal outgrowth at fission plane, *C*, section of epidermis to show epidermal bodies, rhabdites, cilia, *D*, two of tentacular organs, one showing the large inner cells

FIG 3 Dorsal view of *Stenostomum kepneri* *A*, optical section, in outline, of an anterior end, *B*, chain of 3 zooids numbered to indicate relative age of fission planes, *C*, section of epidermis to show cilia and rhabdites, *D*, optical section of posterior end to show position of protonephridiopore

PLATE VII



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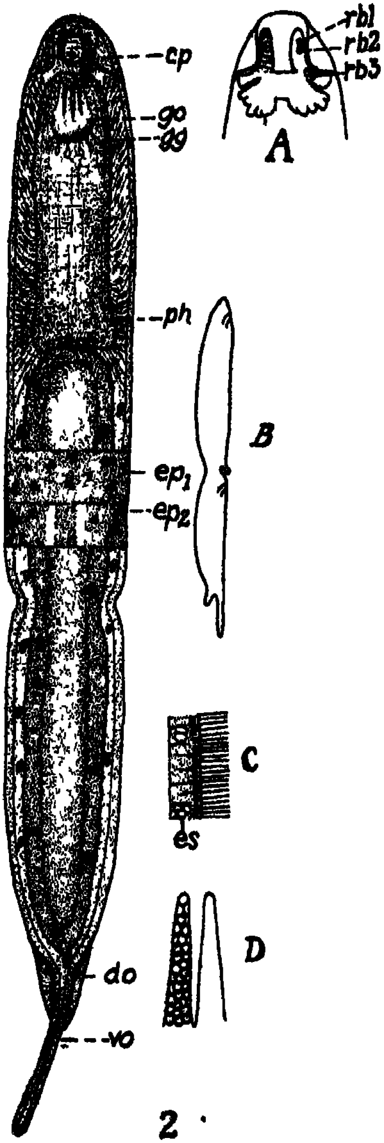

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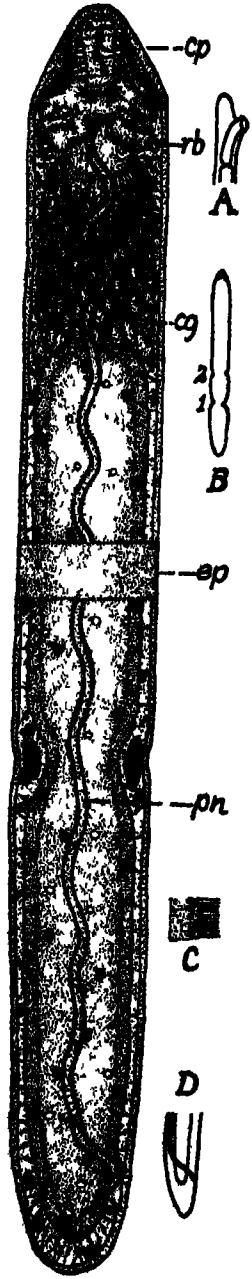

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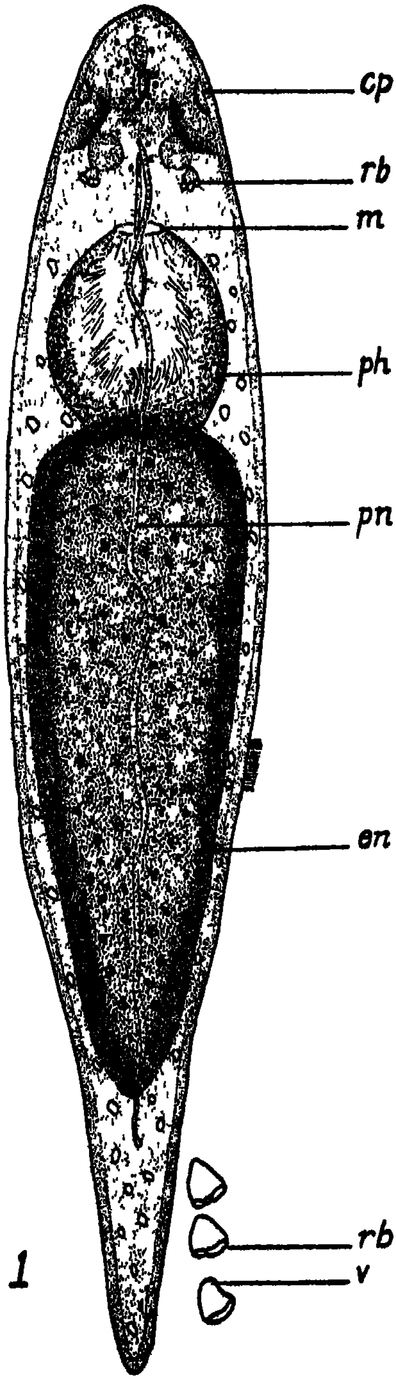
PLATE VIII

FIG 1 * Dorsal view of *Stenostomum ciliatum* *B*, varieties of light refracting bodies showing single, double and triple rod-shaped granules
FIG 2 * Dorsal view of *Stenostomum mandibulatum*

* Redrawn from Kepner and Carter (1931)

PLATE VIII



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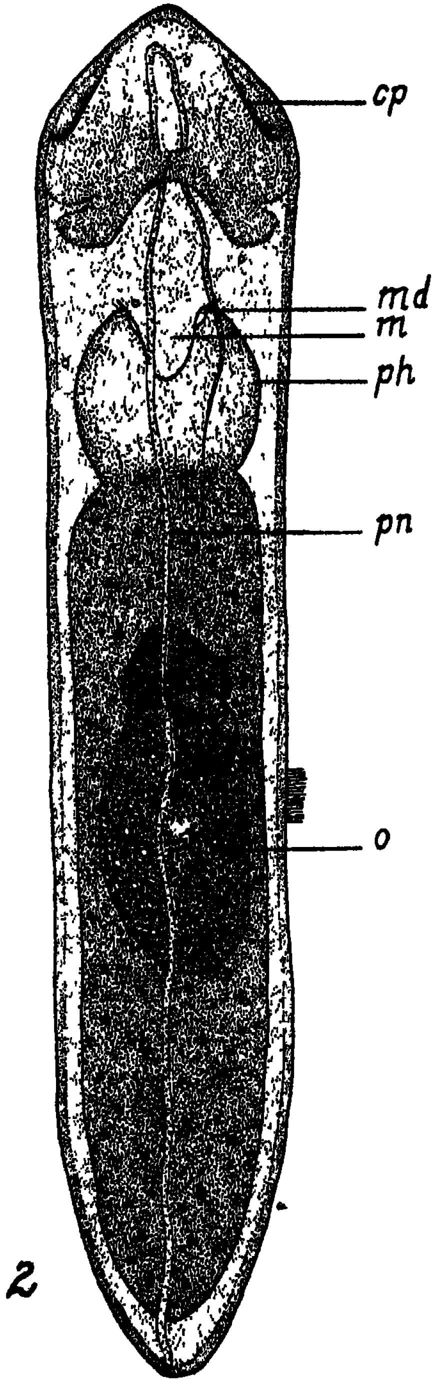

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ERRATUM

On page 303

"Communicated by Albert F Blakesley"
should read
"Communicated by Albert F. Blakeslee"

INFLUENCE OF THE GROWTH OF THE HOST ON OAT SMUT DEVELOPMENT[1]

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(Communicated by Albert F Blakesley)

ABSTRACT

The oat smuts penetrate the oat plant in the seedling stage, the mycelium continuing to develop for several weeks in intimate association with the embryonic host tissues External factors, such as soil temperature and soil moisture, influence penetration

This investigation is concerned with the question whether marked changes in the growth of the host from the seedling stage to maturity, involving the length of the growing period, the height and tillering of the plants, and the development of the panicles and spikelets, influence the final development of the smut organism

Definite strains of oats, varying in their known reaction to specialized races of *Ustilago avenæ* (Pers) Jens and *U levis* (K & S) Magn , were inoculated and grown under varied conditions of illumination and mineral nutrients supplied Under artificial illumination, oats headed out several days to four weeks in advance of the non-illuminated controls, the plants being shorter, with fewer tillers

Plants supplied with modifications of different nutrient solutions showed marked changes in the rate of growth, the extent of elongation of the stems, the amount of tillering, and also the time required from planting to the heading stage

There seemed to be no definite relation between the growth of the host and the ultimate expression of the smut

INTRODUCTION

THE intimate association between host and parasite furnishes fundamental problems for investigation Studies have been made to establish, if possible, some definite connection between their relation and the absorption of mineral nutrients by the host. Profound changes in the growth of plants are induced by modifications of the nutrients supplied. The results are especially evident in experiments involving the elements nitrogen, phosphorus and potassium, although calcium, magnesium and iron produce striking results. In

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[1] Supported in part by a grant from the Penrose Fund of the American Philosophical Society Brooklyn Botanic Garden Contribution No 84

recent years, the important role of traces of copper, manganese, boron and zinc, has been studied.

The present investigation was carried out in order to determine whether changes in the rate of growth of the oat plant, the extent of elongation of the stems, the amount of tillering, the size of the panicles and the number of spikelets, influenced in any way the ultimate development of the oat smuts. Marked variations in plants were obtained by growing different sets under various conditions of illumination and by modifications of the chemical nutrients supplied.

MATERIALS AND METHODS

There are two distinct phases in the establishment of the association between the oat plant and the oat smuts· (1) the phase of penetration of the germ tube of the fungus into the host, (2) the phase of the subsequent development of the mycelium within the host tissues. All the evidence points to penetration taking place in the young seedling stage, usually through the coleoptile while it is 2 cm. or less in length If the mycelium succeeds in reaching the embryonic tissue of the oat plant, it continues to grow along with the latter, and thus a very intimate relation is established between the growing tissues of the two organisms which continues for weeks or even months. At the stage of flowering, with the development of the young ovule, the mycelium of the fungus grows very rapidly and soon passes into the spore-forming stage. The final result is the replacement of the flowering parts by the dusty mass of black spores. In the covered smut, the glumes are left somewhat intact, while in the loose smut they are more or less completely destroyed.

The investigations of Bartholomew and Jones (1923), Jones (1923), and Reed and Faris (1924) have demonstrated that the environal factors of temperature, soil moisture and soil reaction, are very important in the initial penetration of the oat smuts into the host plant. A temperature of approximately 20° C., a low soil moisture content, and a neutral reaction of the soil seem to be most favorable. Sand has proved to be an excellent substratum for germinating the seedlings, having several advantages over soil.

Special strains of oats, as identified by their seed numbers and which have been grown for many years, were used—*Avena sativa* L. Black Mesdag (70), Canadian (119), Danish Island (149), Early Champion (150), Gothland (152), Monarch (161), Scottish Chief (124); *A byzantina* C Koch. Fulghum (129 and 1000); *A. brevis* Roth (289), *A. fatua* L. (968). The seeds were carefully selected and, after the hulls were removed, were inoculated with dry spores and planted in sand in paraffin cups with a moisture content of about 20 per cent of the holding capacity They were germinated at a constant temperature of 20° C. The sand was thoroughly washed and sifted, passing through a 20 mesh sieve, but not through a 40 mesh

The seeds were planted at a depth of about one inch, usually emerging from the sand in four days. Generally, 20 seedlings were grown in each cup. Two or three days later, when the seedlings were about an inch high, they were transplanted to pots or jars, where the plants were grown to maturity. Several cups of seedlings of a variety were needed for each experiment and, on transplanting, the seedlings from each cup of a variety were thoroughly distributed throughout the pots. In the earlier experiments, the plants were grown to maturity in 12 inch azalea pots which were filled with ordinary loam soil to which sand had been added While it was low in fertility, it contained sufficient nutrients for the full development of the control plants. However, responses to the addition of various fertilizers were marked. In 1935 a few preliminary experiments were carried out in which sand was used as a substratum for growing the plants to maturity and in 1936 and 1937 this material was used exclusively. When soil was employed as a substratum there were, of course, many unknown nutritive materials present. To a less extent, this was true also in the sand cultures, since traces of various substances might remain after the washing.

The existence of racial specialization in both species of smuts has been demonstrated by Reed (1924, 1929), Reed and Stanton (1936), Sampson (1925) and Nicolaisen (1931). Some oat varieties are highly susceptible to one specialized race and correspondingly resistant to another Accordingly, the experiments were carried out with specific races of *Ustilago avenæ* (Pers) Jens and *U levis* (K & S.) Magn., specialized Race 1 of each of these species being used in most experiments Avenæ 1 at different times was used to inoculate Canadian, Scottish Chief, Danish Island, and Gothland. With the exception of Scottish Chief, which usually has given a variable percentage of infected plants, all of these varieties are fully susceptible to this race of smut Levis 1 was used to inoculate the susceptible varieties Canadian, Early Champion and Monarch. Danish Island, a variety which does not give 100 per cent infection with this race, was grown in a few experiments *Avena brevis* was also used to some extent. An occasional plant of this oat is attacked, infection, however, practically never occurs on the main stalk, appearing only on the lateral branches, which remain conspicuously shorter than the normal

In some experiments other specialized races were used. Avenæ 9, the Fulghum race, is characterized by its ability to infect the Fulghum oats, although it rarely produces 100 per cent infection Avenæ 10 is a loose smut characterized by its ability to attack Red Rustproof oats and *Avena fatua* (968)

Levis 2 was used to inoculate Monarch and *Avena brevis*, the former being resistant while the latter, under favorable conditions, gives 100 per cent infection. Levis 7 is a Fulghum race of covered smut, characterized by its peculiar ability to attack not only Fulghum strains of oats, but also Black Mesdag. It is unusual, however, to obtain 100 per cent infection on these varieties.

EXPERIMENTAL RESULTS

In the course of investigations, extending over a period of years, on the influence of environal factors on the infection of

TABLE 1

Results for 1933 with *Ustilago avenæ*—Race 1

	Scottish Chief					Gothland				
	Ht Pl, Inches		No Plants	No Inf	Per Cent Inf	Ht Pl, Inches		No Plants	No Inf	Per Cent Inf
	Inf	N				Inf	N			
1 Illuminated	24	32	20	5(1)[1]	25	27	—	20	20	100
2 Non-illuminated	28	34	19	11	58	31	—	20	20	100
3 Nitrogen added	48	59	20	4	20	44	62	19	18	95
4 Lithium chloride added	42	46	20	5	25	33	—	15	15	100
5 Zinc sulphate added	33	37	20	4	20	30	38	20	18	90
6 Potassium added	35	41	20	8	40	27	36	20	19	95
7 Phosphorus added	26	32	20[2]	6	30	30	—	20	20	100
8 Magnesium sulphate added	24	29	20	9	45	22	—	20	20	100

Abbreviations used in tables Ht, height, Pl, plants, Inf, infected, N, normal

Started January 10 Plants grown in 12 inch azalea pots, filled with equal parts of soil and sand

One set illuminated with 200 watt lamps February 1–11 from 4 30 to 10 P M, February 12–April 1 from 5 30 to 10 P M

In the nutrition series, 1 liter of each solution was supplied February 1, 15, March 1, 15, 31 The solutions employed were 1 per cent $NaNO_3$, 0 5 per cent KCl, KH_2PO_4, and $MgSO_4$, 0 1 per cent LiCl and $ZnSO_4$ for the first two applications and 0 05 per cent for the others See Figs 2A and 2B

[1] Figure in parenthesis indicates partially smutted plants

[2] On March 1 received an application of magnesium sulphate in error

TABLE 2

Results for 1933 with *Ustilago levis*—Race 1

	Early Champion					Monarch			
	Ht Pl, Inches		No Plants	No Inf	Per Cent Inf	Ht Pl, Inches	No Plants	No Inf	Per Cent Inf
	Inf	N							
1 Illuminated	24	—	20	20(5)	100	27	20	20	100
2 Non-illuminated	42	51	20	19	95	40	20	20	100
3 Nitrogen added	44	54	19	16	84	51	20	20	100
4 Lithium chloride added	35	50	18	15	83	37	20	20	100
5 Zinc sulphate added	42	42	20	19	95	45	19	19	100
6 Potassium added	38	57	20	15	75	30	20	20	100
7 Phosphorus added	38	48	20	19	95	41	19	19	100
8 Magnesium sulphate added	29	—	19	19	100	27	19	19	100

See footnotes to table 1

TABLE 3

Results for 1935 with *Ustilago avenæ*—Race 1

	Scottish Chief			Gothland		
	No Plants	No Inf	Per Cent Inf	No Plants	No Inf	Per Cent Inf
1 Illuminated	20	16	80	20	20	100
2 Illuminated—$NaNO_3$ added	20	13	65	20	20	100
3 Non-illuminated	18	11	61	20	20	100
4 Non-illuminated—$NaNO_3$ added	20	12	60	19	19	100
5 Full nutrient solution	20	15(1)	75	20	19	95
6 Potassium omitted	20	15	75	20	20	100
7 Phosphorus omitted	20	10	50	20	20	100
8 Full nutrient—LiCl added	20	14	70	20	20	100
9 Full nutrient—$ZnSO_4$ added	20	16	80	20	20	100
10 Lithium nitrate	20	17	85	20	20	100
11 Lithium chloride	20	16	80	20	20	100
12 Zinc nitrate	20	13	65	20	20	100

Started January 15–19 Plants grown in 12 inch azalea pots filled with equal parts of soil and sand One set illuminated with 200 watt lamps February 8–28 from 5 30 to 10 P M, March 1–28 from 6 to 10 P M A 1 per cent solution $NaNO_3$ applied to Exp 2 and 4

Full nutrient solution was 1 g $Ca(NO_3)_2$, 0 25 g each $MgSO_4$ and KH_2PO_4 per liter In Exp 6, NaH_2PO_4 was substituted for KH_2PO_4, and in Exp 7, KCl for KH_2PO_4.

In Exp 8 and 9, 0 25 g LiCl and $ZnSO_4$ per liter were added, and in Exp 10, 11, and 12, solutions containing 0 25 g $LiNO_3$, LiCl, and $Zn(NO_3)_2$ per liter were applied

On February 11 and 12, 500 cc of the solutions were applied to each of the pots, second and third applications of 1 liter were made on February 28 and March 19

See Figs 3A and 3B

TABLE 4

Results for 1935 with *Ustilago avenæ*—Races 9 and 10

	Race 9						Race 10		
	Fulghum (129)			Fulghum (1000)			*Avena fatua*		
	No Plants	No Inf	Per Cent Inf	No Plants	No Inf	Per Cent Inf	No Plants	No Inf	Per Cent Inf
1 Illuminated	20	15	75	19	17	89	19	10(2)	53
2 Illuminated—$NaNO_3$ added	19	16(1)	84	19	16	84	20	15(2)	75
3 Non-illuminated	20	15	75	20	18(2)	90	20	16(4)	80
4 Non-illuminated—$NaNO_3$ added	20	16(5)	80	18	15(4)	83	18	15	83
5 Full nutrient solution	19	14(1)	74	20	17(4)	85	18	15(7)	83
6 Potassium omitted	20	16(3)	80	19	15	79	20	10(1)	50
7 Phosphorus omitted	20	16(1)	80	20	19(3)	95	20	12(1)	60
8 Full nutrient—LiCl added	20	19(1)	95	19	17(3)	89	20	11(2)	55
9 Full nutrient—$ZnSO_4$ added	20	16(3)	80	20	20(5)	100	20	10(2)	50
10 Lithium nitrate	20	19(5)	95	18	14(2)	78	20	14	70
11 Lithium chloride	20	17	85	19	16(3)	84	20	11	55
12 Zinc nitrate	20	17(2)	85	19	15(1)	79	20	10(2)	50

See footnotes to table 3.

oats by the smuts, on the racial specialization of the smuts, and the inheritance of smut resistance in oat hybrids, many experiments have been carried out which had a bearing on some phases of the present work The main experiments, however, were made in 1933, 1935, 1936 and 1937 In 1933 and 1935 the inoculated plants were grown in a mixture of loam soil and sand, while in 1936 a clean grade of builders' sand and in 1937 white beach sand was used as the sub-

TABLE 5

RESULTS FOR 1935 WITH *Ustilago levis*—RACE 1

	Danish Island			Monarch				*Avena brevis*		
	No Plants	No Inf	Per Cent Inf	Ht Pl, Inches	No Plants	No Inf	Per Cent Inf	No Plants	No Inf	Per Cent Inf
1 Illuminated	20	7	35	36	19	19	100	12	0	0
2 Illuminated—NaNO₃ added	18	8(4)	44	36	20	20	100	19	8(8)	42
3 Non-illuminated	20	7	35	47	18	18	100	20	10(8)	50
4 Non-illuminated—NaNO₃ added	20	7	35	50	18	18(1)	100	18	2(2)	11
5 Full nutrient solution	20	6	30	46	20	20	100	18	3(3)	17
6 Potassium omitted	20	4	20	46	19	19	100	14	5(5)	36
7 Phosphorus omitted	20	3	15	50	20	20	100	19	6(5)	32
8 Full nutrient—LiCl added	20	6	30	50	20	20	100	17	6(6)	35
9 Full nutrient—ZnSO₄ added	19	5	26	46	18	16	89	17	3(3)	18
10 Lithium nitrate	20	6	30	46	20	20	100	18	4(3)	22
11 Lithium chloride	20	5	25	47	20	20	100	14	0	0
12 Zinc nitrate	19	7	37	47	20	20	100	19	6(6)	32

See footnotes to table 3

TABLE 6

RESULTS FOR 1935 WITH *Ustilago levis*—RACE 7

	Black Mesdag			Fulghum (120)			Fulghum (1000)				
	No Plants	No Inf	Per Cent Inf	No Plants	No Inf	Per Cent Inf	Ht. Pl., Inches		No Plants	No Inf	Per Cent Inf
							Inf	N			
1 Illuminated	20	2(2)	10	20	4	20	30	35	20	8	40
2 Illuminated—NaNO₃ added	20	8(8)	40	20	11(6)	55	37	41	20	13(13)	65
3 Non-illuminated	20	5	25	20	8(4)	40	36	40	20	9(1)	45
4 Non-illuminated—NaNO₃ added	20	9(6)	45	20	9(9)	45	43	49	19	7(6)	37
5 Full nutrient solution	20	5(3)	25	20	9(5)	45	45	48	19	11(6)	58
6. Potassium omitted	18	7(7)	39	20	8(5)	40	46	49	20	9(6)	45
7 Phosphorus omitted	20	3	15	20	6(2)	30	37	41	20	7(4)	35
8 Full nutrient—LiCl added	19	6(2)	32	19	7(6)	37	44	48	16	8(4)	50
9 Full nutrient—ZnSO₄ added	20	4	20	20	9(4)	45	32	39	20	12(6)	60
10 Lithium nitrate	20	4(2)	20	21	7(5)	33	39	45	20	7(3)	35
11 Lithium chloride	20	2	10	19	6(3)	32	38	41	20	8(6)	40
12 Zinc nitrate	20	1	5	20	8(5)	40	39	48	20	10(3)	50

See footnotes to table 3

TABLE 7

Results for 1936 and 1937 with *Ustilago avenæ*—Race 1

	Year	Scottish Chief					Gothland				
		Ht Pl, Inches		No Plants	No Inf	Per Cent Inf	Ht Pl, Inches		No Plants	No Inf	Per Cent Inf
		Inf	N				Inf	N			
1 No nutrient	1936	8	12	20	14(1)	70	11	12	18	17	95
	1937	7	13	14	11	79	12	—	15	15	100
2 Full nutrient	1936	38	51	20	12(1)	60	39	—	20	20(1)	100
	1937	22	24	15	12	80	25	—	15	15	100
3 No nitrogen	1936	9	13	20	12	60	12	—	20	20	100
	1937	10	11	15	14	93	14	—	15	15	100
4 Excess nitrogen	1937	31	39	15	12(1)	80	29	—	15	15	100
5 No potassium	1936	41	49	20	15(1)	75	43	—	20	20(1)	100
	1937	25	26	15	13	87	22	—	14	14	100
6 Excess potassium	1936	41	53	20	14	70	43	—	20	20	100
	1937	26	32	12	11(1)	92	25	—	13	13	100
7 No phosphorus	1936	11	16	20	14	70	15	22	19	18	95
	1937	15	23	15	13	87	22	—	15	15	100
8 Excess phosphorus	1936	38	47	20	15	75	45	—	18	18	100
	1937	24	34	15	12	80	24	—	13	13	100

In 1936, duplicate sets were started on January 9 and 23 Plants were grown in 3 gallon crocks filled with well washed builders' sand

The full nutrient solution consisted of 1 g Ca(NO$_3$)$_2$, 0 25 g each MgSO$_4$ and KH$_2$PO$_4$ per liter In Exp 5, NaH$_2$PO$_4$ was substituted for KH$_2$PO$_4$, and in Exp 7, KCl for KH$_2$PO$_4$. In Exp 6 and 8, 0 75 g of KCl and NaH$_2$PO$_4$ per liter were added

One liter of each solution was applied on January 22 in the first series, and in the first and second series on February 6, 20, and March 17.

In 1937, the experiments were started January 7 Plants were grown in 3 gallon crocks filled with well washed beach sand The same solutions were used as in the previous year In Exp 4, 0 75 g NaNO$_3$ per liter was added

One liter was applied to the cultures on January 21, February 1, 15, and March 1

See Fig 4

stratum. Brief reports on the results obtained have been made (Reed 1936, 1937).

The data are recorded in tables 1 to 9, and Figs. 1 to 4 illustrate the characteristics of the plants grown in some of the experiments. In the tables, information is given regarding the varieties of oats and the races of smuts used, with the percentages of infection obtained The notes supply miscellaneous details regarding the substratum in which the plants were grown, the composition of the nutrient solutions and their method of application, as well as information regarding the periods of illumination.

TABLE 8

RESULTS FOR 1936 AND 1937 WITH *Ustilago levis*—RACE 1

	Year	Danish Island					Monarch				
		Ht Pl, Inches		No Plants	No Inf	Per Cent Inf	Ht Pl Inches		No Plants	No Inf	Per Cent Inf
		Inf	N				Inf	N			
1 No nutrient	1936	15	14	20	2	10	13	7	19	18	95
	1937	10	12	15	8	53	13	—	15	15	100
2 Full nutrient	1936	37	52	20	4	20	31	56	20	19(1)	95
	1937	23	30	12	3	25	31	—	15	15	100
3 No nitrogen	1936	17	15	20	1	5	13	—	20	20	100
	1937	13	16	15	7	47	11	—	14	14	100
4 Excess nitrogen	1937	32	35	15	10	67	37	—	15	15	100
5 No potassium	1936	35	50	20	3	15	42	—	20	20	100
	1937	22	32	15	6	40	31	—	15	15	100
6 Excess potassium	1936	38	51	19	2	11	51	—	20	20(2)	100
	1937	27	38	15	9	60	37	—	14	14	100
7 No phosphorus	1936	16	18	20	4	20	14	16	20	17	85
	1937	19	33	15	8	53	17	—	14	14	100
8 Excess phosphorus	1936	33	53	20	2	10	43	34	20	19	95
	1937	26	37	15	10	67	30	—	14	14	100

See footnotes to table 7

In most of the tables, data regarding the growth of the plants are supplied The length of the main stem and the extent of tillering were used as criteria in determining the influence of the varied conditions Usually, in such experiments, the dry weight of the plants is determined In these experiments, however, such data would be quite unreliable on account of the great differences in the dry weight of smutted and normal plants

EXPERIMENTS ON ILLUMINATION

An experiment was carried out in 1929 in which Canadian was inoculated with Avenæ 1 and Levis 1. The seed was

TABLE 9

RESULTS FOR 1936 AND 1937 WITH *Ustilago levis*—RACE 7

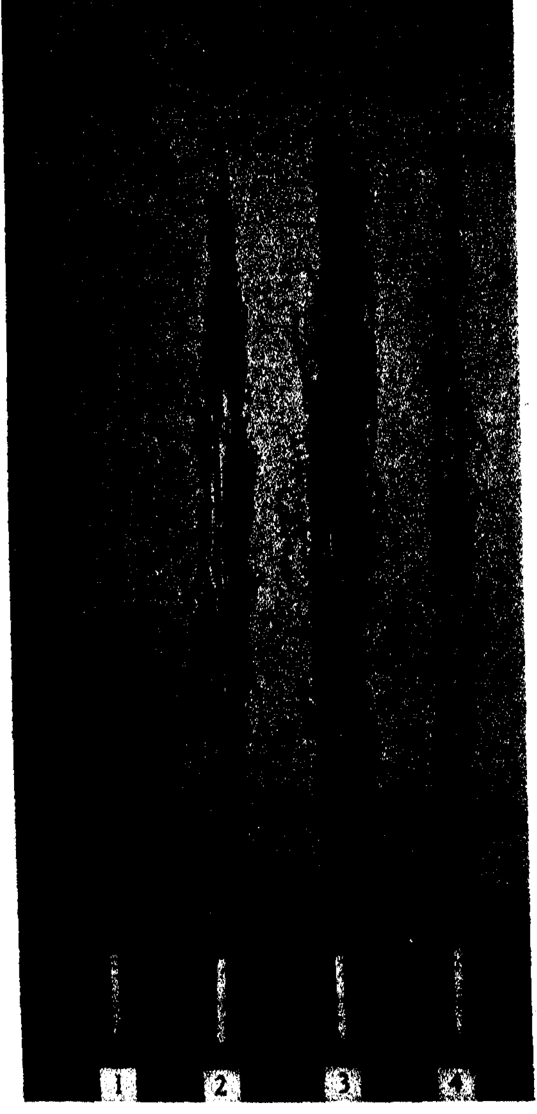
	Year	Black Mesdag					Fulghum (1000)				
		Ht Pl, Inches		No Plants	No Inf	Per Cent Inf	Ht Pl, Inches		No Plants	No Inf	Per Cent Inf
		Inf	N				Inf	N			
1 No nutrient	1936	14	17	20	15	75	15	14	20	8(3)	40
	1937	13	10	13	11(1)	85	13	18	15	11	73
2 Full nutrient	1936	39	42	20	9(1)	45	32	42	20	9(8)	45
	1937	30	27	15	14(2)	93	29	28	14	12(4)	86
3 No nitrogen	1936	18	12	20	18	90	17	18	19	8(3)	42
	1937	15	15	15	14	93	15	15	14	8(1)	57
4 Excess nitrogen	1937	34	—	14	14(1)	100	26	30	15	14(7)	93
5 No potassium	1936	42	43	20	10	50	—	46	20	3(3)	15
	1937	32	31	14	12	86	25	34	15	12(4)	80
6 Excess potassium	1936	40	39	20	15(2)	75	34	37	20	9(6)	45
	1937	34	36	15	12	80	27	44	15	14(6)	93
7 No phosphorus	1936	15	14	20	13	65	11	16	20	8(3)	40
	1937	22	23	15	13	87	19	25	15	11(2)	73
8 Excess phosphorus	1936	39	39	20	11	55	31	39	20	6(1)	30
	1937	33	22	15	13	87	26	32	15	14(3)	93

See footnotes to table 7

ruary 10 and one set of seedlings was grown
usual greenhouse conditions and another was arti
inated from February 10 to April 1. The charac
rences in the plants grown under the two conditio

1. Canadian inoculated with *Ustilago avenæ* 1. 1, non-illumin
2, illuminated.

ated in Fig. 1, the photograph being taken May 10
ime, all the plants in the illuminated series were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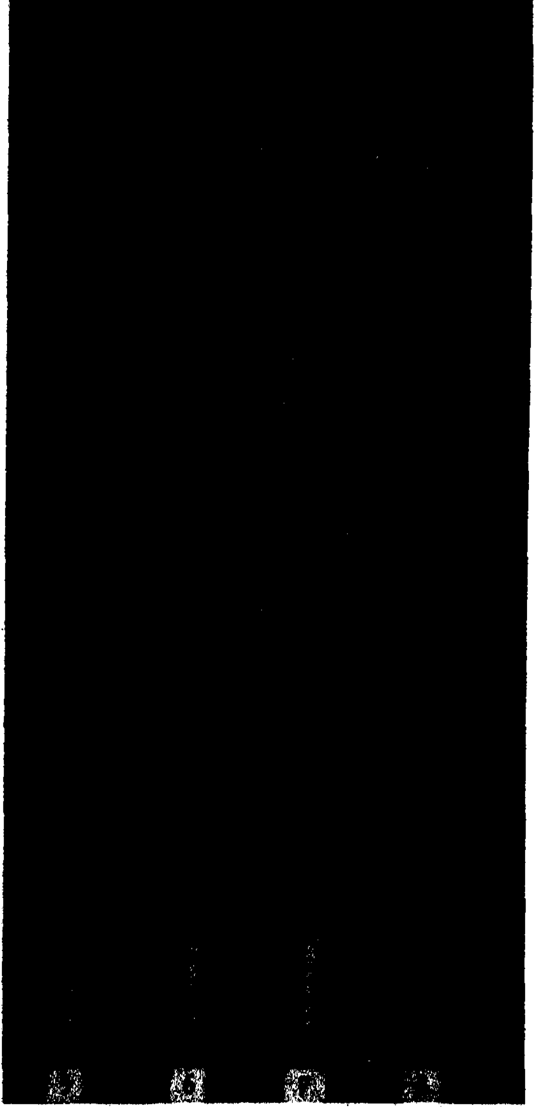

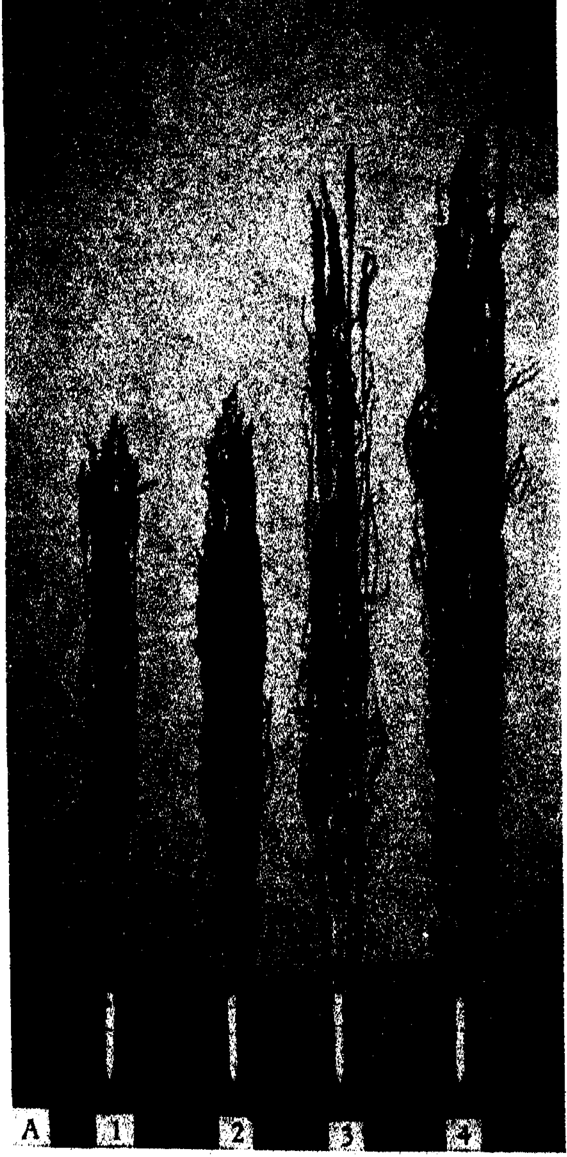
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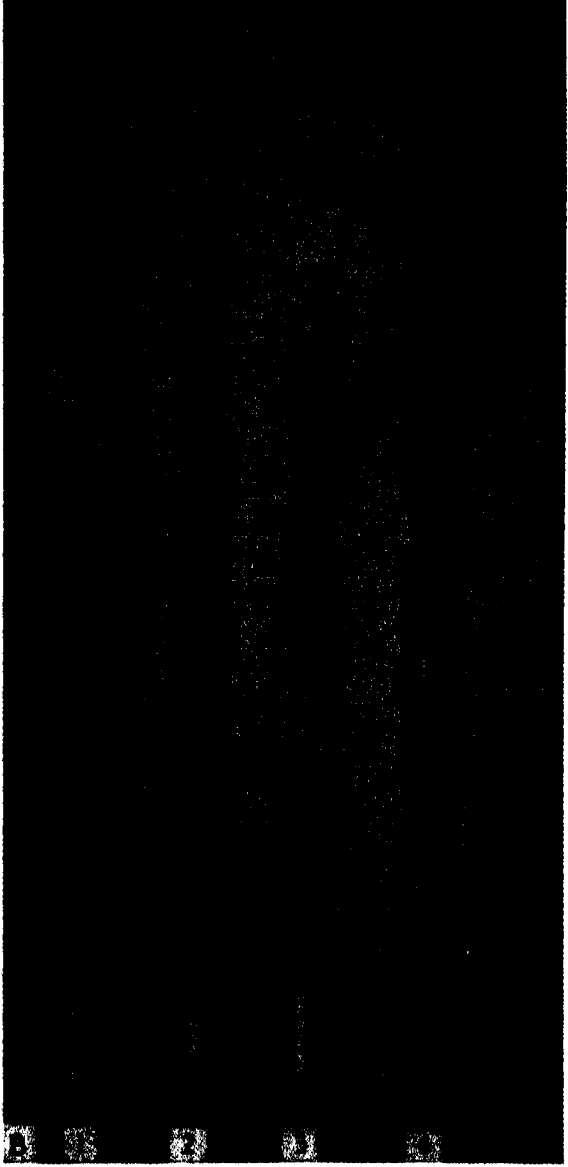

. 4. Influence of nutrition on infection of Monarch and C

Additional experiments were carried out in 1933, the data being recorded in Tables 1 and 2, and some of the plants are illustrated in Figs. 2A and 2B A final series was grown in 1935, the data being recorded in Tables 3 to 6, and some of the plants illustrated by Figs 3A and 3B

The effect of illuminating the plants was to shorten greatly the time required for them to reach the heading stage. The difference varied with the varieties, but usually amounted to from two to four weeks. The illuminated plants produced relatively few tillers In contrast, the non-illuminated plants, varying with the variety, usually produced one or more side branches, the main branches also being considerably taller In 1935, a 1 per cent solution of sodium nitrate was added to one set of the plants in both series The effect of the nitrogen was to increase the amount of growth and the extent of tillering.

These marked variations in the rate and extent of growth of the oat varieties showed no conspicuous difference in their effect upon the percentage of infected plants In 1929, all the plants of Canadian in both series inoculated with Avenæ 1 and Levis 1 gave 100 per cent infection Gothland, inoculated with Avenæ 1 in 1933 and 1935, gave 100 per cent infection in practically every experiment Scottish Chief in 1933 gave somewhat higher percentages of infection in the non-illuminated as compared with the illuminated series, while in 1935 the reverse was true The percentages of infection in the illuminated and non-illuminated plants supplied with sodium nitrate in 1935 were practically the same

Usually, all of the plants of Monarch inoculated with Levis 1 were infected, and Early Champion also gave high percentages of infection. In 1935 no infected plants of *Avena brevis* were recorded in the illuminated series, while in the non-illuminated 50 per cent were smutted. However, in the corresponding series supplied with sodium nitrate 42 per cent infection of the illuminated plants was obtained and only 11 per cent of the non-illuminated. Danish Island in 1935 gave essentially the same result in all of the experiments.

In 1935, Avenæ 9 gave practically the same results on the two strains of Fulghum in the illuminated as compared with the non-illuminated plants, somewhat higher percentages being obtained in the series supplied with sodium nitrate. Avenæ 10 on *Avena fatua* gave somewhat higher percentages of infection in the non-illuminated series. Levis 7 seemed to give no consistent differences in the number of infected plants of Black Mesdag and the two strains of Fulghum in the illuminated and non-illuminated series.

INFLUENCE OF NUTRITION

Experiments on the influence of various nutrient salts, particularly those which contained nitrogen, potassium and phosphorus, were carried out. The extensive data obtained are recorded in tables 1 to 9 Essential details regarding the experiments are given in the footnotes. Figs. 2A to 4 illustrate some of the cultures grown in the different series

The addition of nitrate to the cultures increased the height of the plants, bearing longer and broader leaves of a deeper green color The plants tillered extensively, and the panicles produced were larger, with numerous spikelets The difference between the plants supplied with nitrate was more marked in the sand cultures of 1936 and 1937 than in the soil cultures of the earlier years. Gothland, in 1936, growing in sand without any nutrient solution, averaged 11 inches in height, without nitrogen but with potassium and phosphorus supplied, 12 inches, while in the full nutrient solution the average height was 39 inches. An examination of the tables will reveal similar differences in the growth of the other oat varieties

The results of growing the plants with and without phosphorus were also striking, particularly in the sand cultures. When Gothland was grown in a full nutrient solution, the plants averaged 39 inches in height, while in the experiment without phosphorus they averaged 15 inches.

There were no marked differences in the plants grown with and without a supply of potassium, especially in the soil cultures. In the sand cultures of 1936, excess potassium appeared to make a difference in the total amount of growth.

The profound changes in the rate and extent of growth of the varieties in the various experiments did not seem to affect, in any significant way, the percentages of infection Gothland inoculated with Avenæ 1 usually gave 100 per cent infection. Scottish Chief continued to give variable percentages of infection, but a detailed examination of the tables reveals no consistent relation to the supply of nitrogen, phosphorus or potassium It may be noted, however, that the percentage of smutted plants was higher in 1937 than in previous years

In 1935, two strains of Fulghum were inoculated with Avenæ 9, and *Avena fatua* with Avenæ 10. There were slight differences in the percentage of infection in the different experiments, but no indication that they were correlated in any way with the nutrients supplied

Monarch and Early Champion, inoculated with Levis 1, usually gave 100 per cent infection Danish Island, in 1935 and 1936, gave variable percentages of infection, but no relation to the nutrients supplied is indicated. In 1935 smutted plants of *Avena brevis* appeared in all of the experiments, the percentage varying from 17 to 36. In every case the infected plants were partially smutted, the main stem being normal

Avena brevis, inoculated with Levis 2 in 1935 and 1937, gave complete infection of every plant in the experiments, while negative results were obtained on Monarch, except for one smutted plant in a single experiment which, however, may have been a stray infection with Levis 1. Black Mesdag and two strains of Fulghum were inoculated with Levis 7. There were some minor differences in the percentages of infection in the experiments, but no clear-cut relation to the nutrients supplied.

In some experiments, lithium chloride, lithium nitrate, zinc nitrate and zinc sulphate were applied to some of the cultures, the most extensive data being obtained in 1935 with all the different races of smut. The salts of lithium and zinc were likely to prove somewhat injurious to the plants and consequently dilute solutions had to be used. The nitrates of both lithium and zinc produced a luxuriant growth of the varieties, indicating the effect of the nitrogen.

The data are recorded in Exps 8 to 12 in Tables 3 to 6. In these experiments Gothland, inoculated with Avenæ 1, gave 100 per cent infection, while Scottish Chief varied from 65 to 85 per cent Avenæ 9 on the two strains of Fulghum gave infections varying from 78 to 100 per cent, the percentage of infection of *Avena fatua* inoculated with Avenæ 10 varied from 50 to 70

Monarch, inoculated with Levis 1, usually gave 100 per cent infection, while the percentage of smutted plants of Danish Island varied from 25 to 37, and of *Avena brevis* from 0 to 35 per cent. It may be noted, in connection with Table 5, that no stooling occurred in the two experiments where no infected plants were recorded. All the plants of *A. brevis* inoculated with Levis 2 were infected, while Monarch gave negative results Levis 7, on the two strains of Fulghum, gave percentages varying from 32 to 60, and on Black Mesdag from 5 to 32

DISCUSSION

On the basis of the experimental data presented, the growth of the oat plant, greatly influenced by variations in illumination and modifications of the nutrients supplied, has no significant effect on the development of the oat smut within the tissues. Susceptible varieties such as Gothland, Monarch and *Avena brevis*, inoculated with specific races of the smuts, were fully infected whether the plants were 12 inches or less in height with no tillers and few spikelets in the panicles, or 4 to 5 feet tall with many side branches bearing broad leaves and large panicles with many spikelets Although the growing period may have varied from a few weeks to several months, there was no evidence of any change in the susceptibility or resistance of these varieties to the races with which they were inoculated

Scottish Chief inoculated with Avenæ 1, Danish Island and *Avena brevis* inoculated with Levis 1, Fulghum inoculated with Avenæ 9, and *A. fatua* inoculated with Avenæ 10, in experiments extending over several years, have given a variable percentage of infected plants Such varieties, perhaps, might be expected to show greater responses to specific changes in growth, resulting in a significant change in the number of smutted plants Fulghum and *A brevis* also tiller out very extensively, and thus may give a higher percentage of partially infected plants There is no definite indication, however, that any of these varieties, inoculated with the specific races of smuts, have changed in their behavior The percentage of infection still continued variable and without any relation to the particular treatment applied In two experiments in 1935 (Table 5), *A. brevis* gave negative results with Levis 1. It is characteristic, however, of this species to be infected with this race of smut only in the lateral branches and, unless tillering takes place, no evidence of infection may appear

Lasser (1937) has studied the influence of light and yarovization on the infection of certain cereals by the smuts No conspicuous differences in the behavior of varieties of spring wheat, inoculated with *Tilletia tritici*, were recorded under any of the conditions, high percentages of infection usually being obtained in all of the experiments On the other hand, four varieties of winter wheat, when subjected to yarovization, gave lower percentages of infection than the non-yarovized plants. However, no important variations in the percentage of infection under different conditions of illumination were recorded. Neither yarovization nor illumination had any obvious effect in influencing the amount of infection with loose smut of wheat and of barley. Lasser also recorded marked differences in the development of oat plants under various conditions of illumination and yarovization, but no significant variations in the percentages of smut were recorded.

The experiments of Gaines (1923) and Smith (1932) indicated that the long growing period of fall-planted wheat, as compared with spring-planted, may exert an influence upon the subsequent development of bunt Faris (1924) also offered some evidence for a similar condition in the covered smut of barley.

Many investigations have been carried out on the influence of fertilizers and mineral nutrients on rust and powdery mildew infection of various cereals. Spinks (1913) concluded that susceptibility to yellow rust on wheat and powdery mildew on wheat and barley was increased by supplying large amounts of available nitrogen, ammonium sulphate and sodium nitrate being equally effective Potash salts appeared to decrease the susceptibility, although it did not counteract the effect of large quantities of nitrogeneous manures Lithium salts seemed to produce immunity, while the nitrates of lead and zinc rendered the plants very susceptible. A resistant variety, however, tended to retain its immunity to yellow rust even when supplied with an excess of nitrogeneous materials Many other investigators have found similar effects produced by nitrogeneous fertilizers Gassner (1915), Stakman and Aamodt (1924) and Armstrong (1922), as well as others, suggest that the spread of rust on plants supplied with nitrogenous fertilizers is favored because they are more vigorous, mature later, and provide excellent conditions for its development Turner (1922), Trelease and Trelease (1928) and Lowig (1933) found responses in the reaction of some of the cereals, grown in various nutrient cultures, to the powdery mildew Hursh (1924) and Lowig (1933) called attention to the changes in tissue structure which might account for the difference in infection of plants supplied with nitrates, as compared with those supplied with potash

In all these experiments with rusts and powdery mildews it may be that the influence of fertilizers and various chemical elements may be concerned as much with providing conditions favorable for penetration as for exerting an influence on the fungus after it has once entered.

In considering the influence of the growth of the host on the subsequent development of certain diseases, it is important to recognize the difference in the relations between the parasites and their host The rusts and powdery mildews of cereals produce a very local infection. A small area is attacked and relatively few cells are invaded by the mycelium at any given point. The extent of the attack on the host will depend on the number of viable spores which are distributed over the surface of the leaves. The cycle of development also is very brief. Under favorable conditions it is three to four days in the powdery mildew, while in the rusts it may be six to ten days. It also may be noted that in the rusts the mycelium develops in the parenchyma tissues of the interior of the leaf, while the powdery mildew is a surface parasite, sending haustoria into the epidermal cells. Thus, the relations of rusts and powdery mildews to their hosts are quite different from those of the oat smuts, which penetrate the seedling stage and, if successful, continue their development for long periods of time in close association with the embryonic tissue.

Our investigations emphasize the importance of environal factors, such as soil temperature and the water content of the substratum, during the period of germination of inoculated seed, for the infection of a susceptible oat variety. The subsequent development of the oat plant does not seem to influence the fundamental resistance or susceptibility to the smuts.

Accordingly, the conditions during the phase of penetration of parasites must be controlled properly in order to draw any final conclusions regarding the influence of later growing conditions on their development.

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A STUDY OF THE ABSOLUTE DIMENSIONS OF ECLIPSING VARIABLES

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ABSTRACT

For more than eighty per cent of eclipsing variables only the relative dimensions are known, as determined from photometric observations Our ignorance of the masses, the result of a lack of spectroscopic observations, has been the chief handicap to a determination of absolute dimensions (radii, masses, and densities)

The author has developed a formula for deriving the masses in an eclipsing system when the relative dimensions of the system and one of the spectra are known The formula is based on the laws of motion, the law of black body radiation, and the mass-luminosity relation (here considered empirically) The masses computed from the formula and observed directly are shown to be in agreement, with some exceptions which are discussed in detail

The observed masses are used to derive a radiation temperature scale for eclipsing stars Finally, fifteen binary systems, of which two are spectroscopic binaries, not established eclipsing systems, are evaluated in respect to their absolute dimensions

The paper discusses some of the largest stars the radii of which have ever been derived and some of the largest masses known for eclipsing variables Very low temperatures are involved for some of the fainter components

1. THERE are only 35 eclipsing variables for which the masses are known, computed on the double basis of the orbital velocities of both components and the relative elements derived from the light curve. There are, however, more than 25 eclipsing variables for which the orbital radial velocity for only one of the components has been observed, and there are more than 200 such systems for which only the relative dimensions are known.

2. Since general recognition of Eddington's mass-luminosity relation, the eclipsing variables have often been used to compare the observed with the computed values. The comparisons have been made by the method proposed by Eddington himself: the absolute magnitude is derived, and,

after application of a temperature correction, the bolometric magnitude so computed is compared with the magnitude predicted from the mass In this way it was found that the mass-luminosity relation is of the same character for both eclipsing variables and double stars, the latter, however, show a somewhat narrower range—not more than 10—in their masses, so that a direct comparison between the two groups of binaries can be made only for a limited number of systems

3 Usually in a study of eclipsing variables one adopts a temperature scale based on general spectroscopic observations These variables, however, give an independent derivation of the temperature scale if the parallax is known The possibility of using this method was suggested by Russell, Dugan, and Stewart[1] in 1927 for β Aurigæ, and it has been applied independently by the author[2] for more than thirty components of eclipsing systems

4 The three important problems, mentioned above under (1), (2), and (3), can be treated now in a new way[*] A partial discussion of the method has previously been given by the author[3] We write the following relations for a double star

$$m_1 + m_2 = c_1 A^3 P^{-2} = m_1(1 + \alpha), \tag{1}$$

$$L = c_2 R^2 T_e^4, \tag{2}$$

$$L = c_3 m^{1+\nu}, \tag{3}$$

$$R = rA \tag{4}$$

We replace A in (1) by R from (4), then, replacing R by L and T_e from (2), and, finally, replacing L by m from (3), we obtain the following general formula for computing the mass (m) of a component in a binary system for a given period (P), temperature T_e, mass ratio (α), and radius of the star in the unit of distance between the centers (r)

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[*] *See* partial investigations of these problems by Holmberg,[4] Pilowski,[5] Kreiken,[6] and Elsworth[7]

[1] *Astronomy*, Russell, Dugan, and Stewart, II, 750, 1927.

[2] *A N*, 248, 213, 1933

[3] *P A A S*, 9, 121, 1938

[4] *Lund Medd*, Series 2, No 71, 1934

[5] *A N*, 261, 18, 1936

[6] *A N*, 259, 349, 1936

[7] *Journ d Obs*, 21, No 1, 1938

$$\log m = 2/(7 + 3p)[- \log c_1 + 3/2 \log c_2 - 3/2 \log c_3 + \log (1 + \alpha) + 2 \log P + 6 \log T_e + 3 \log r] \quad (5)$$

If the period is expressed in days, masses and distance between the centers (A) in solar units, then c_1 is 74.4^{-1} If L, R, and T_e are expressed in solar units, then $c_2 = 1$. The third equation is the mass-luminosity relation, and if here again all quantities are expressed in solar units, $c_3 = 1$ If, however, every quantity in (1), (2), and (3) is expressed in grams, seconds, ergs, and degrees, then $c_1 = 5.93 \times 10^8$, $c_2 = 7.21 \times 10^{-4}$, and $c_3 = 4.83 \times 10^{-67}$. It is much more convenient to use the first system of units Then we have

$$\log m = 2/(7 + 3p)[1.871 + \log (1 + \alpha) + 2 \log P + 6 \log T + 3 \log r] \quad (6)$$

Of the three equations (1), (2), and (3), the two former are exact, the third is only an approximation, for p is not exactly known, and is probably not constant throughout the whole interval of the masses used for eclipsing variables Double star material gives $p = 0$ and $p = 0.2$, which are equally good first approximations See, for example, Parenago[8]

It is evident that the quantity α influences m in a very slight manner, for it is always less than 1. It will be shown below that α can be deduced, within the necessary limits of accuracy, from the data of the light curve. The quantities P and r are derived from the light curve, so that if the temperature can be adopted from the spectrum, we will be able to compute the masses without being dependent on spectroscopic orbital velocities Thus Problem (1) can be extended over almost three hundred eclipsing variable stars * Problem (2) can be treated differently. instead of comparing absolute

[8] *Rus Ast Journ*, 14, 33, 1937

* The writer is now engaged in such computations

magnitudes we can compare masses. Problem (3) can also be treated in a new way, as we have pointed out above.

TABLE I(*a*)

THE DATA OF 35 ECLIPSING SYSTEMS

Star	Period	Spectra	Amplitudes			Masses	
	d		*A*	*A*		m_1	m_2
S Ant	0 65	A8+A8	0 16−0 09		*pl*	0 75○	0 42○
σ Aql	1 95	B8, B8+B8	0 44	0 40	*v*	6 19	5 14
TT Aur	1 33	B5, B3+B3	0 96	0 37	*p*	6 70	5 3
WW "	2 53	AO, A7+A7, A4sp	0 64	0 52	*v*	2 20	1 90
AR "	4 13	B9, AO+AO	0 74	0 54	*p*	2,68	2 50
β "	3 91	AOp+AOp, A1np	0 09	0 09	*pl*	2 40	2 36
ζ "	972	KO+B1, cK4+B, K5+B9	0 70	—	*p*	16 4	9 5
ι Boo	0 27	G2+G2	0 42	0 42	*p*	0 64	0 64
RS CVn	4 80	F8, F4n+dG8	1 92	0 08	*p*	1 85	1 74
TV Cas	1 81	B9, AO+AO, B5+B9	1 05	0 09	*v*	1 83	1 01
AO "	3 52	BO, O8, 5nk+O8, 5nk	0 2	0 2	*pl*	36 3	36 3
UW CMa	4 39	Oe, O7sfk+O7sfk, O9sfk	0 34	0 33	*p*	40 3	30 8
VV Cep	7430	Map, M2e+B9	0 8	—	*p*	44 5	35 6
AH "	1 77	B3, BOnk+BOnk	0 22	0 16	*v*	14 6	12 7
U CrB	3 45	B8, B5+B9	1 02	—	*v*	5 3	2 0
Y Cyg	3 00	B2, O9nnk+O9nnk	0 60	0 40	*v*	17 6	17 4
GO "	0 72	AO, B9n+AOn	0 54	0 23	*p*	1 04	0.88
MR "	1 68	AO, AO+AO	0 71	0 15	*p*	3 03	2 59
YY Gem	0 81	dM1e+dM1e	0 6	0 6	*p*	0 63	0 57
Z Her	3 99	F5p, F2p+F2p	0 80	0 12	*v*	1 6	1 3
RX "	1 78	AO, AO+AO	0 68	0 60	*v*	2 2	1 9
TX "	2 01	A5, A2+A2	0 70	0 34	*p*	2 06	1 77
u "	2 05	B3, B3+B3	0 68	0 28	*pl*	7 52	2 87
RT Lac	5 07	G5+K1	1 06	0 61	*v*	5 00	1 00
AR "	1 90	G5, G5+KO, G3+G2	1 03	0 29	*p*	1 42	1 41
CM "	1 60	A2+A2	0 85	0 20	*p*	2 00	1 50
U Oph	1 68	B8, B5nk+B5nk	0.69	0 59	*v*	5 36	4 71
WZ "	4 16	GO, GO+GO	0 74	0 72	*v*	1 41	1 35
AG Per	2 03	B3, B3k+B3k	(0 30)	(0 23)	*p*	5 2	4 6
V Pup	1 45	B1, B1+B3	0 64	0 53	*p*	21 2	16 3
U Sge	3 38	B9, B9+G2	2 88	0 07	*v*	6 70	2 03
W UMa	0 33	GO, F8p+F8p	0.76	0 68	*p*	0 75	0 54
TX "	3.06	B9+A3	2 49	—	*p*	3 0	1 0
Z Vul	2 45	B3, B3+B3	1 63	0 14	*v*	5.34	2 36
RS "	4 48	B8, B8+B9	0 73	0 08	*v*	5 26	1 64

The observational material is given in Tables I(*a*) and I(*b*) for thirty-five eclipsing stars. The period (Table I(*a*), column 2) is the essential element in Formula (6). The spectra (column 3) are taken from classifications made at different observatories, the first determination usually refers to the Harvard classification. If both components are classified, they are connected with a plus sign One sees from the column of spectra how flexible are some of the types, and it has been difficult to give preference to any one system of classification. From considerations developed below, how-

TABLE I(*b*)

THE DATA OF 35 ECLIPSING SYSTEMS

Star	α	$1 + k$	Ell	r^{-1}	L_1	No	α_c
S Ant	0 56	1 73	0 78	2 80	0 67	1	0 73
σ Aql	0 81	2 00	0 95	4 45	0 57	1	0 89
TT Aur	0 79	1 86	0 83	3 88	0 73	3	0 63
WW "	0 86	1 96	1 00	5 62	0 58	2	0 87
AR "	0 93	2 09	1 00	9 56	0 51	1	0 98
β "	0 99	2 00	0 98	6 80	0 50	3	1 00)
ζ "	0 59	1 025	1 00	5 01	(0 52)	3	(0 97
ι Boo	1 00	1 86	0 92	3 20	0 50	1	1 00
RS CVn	0 94	2 56	(0 93)	5 02	0 73	5	0 63
TV Cas	0 55	2 22	0 95	4 00	0 92	8	0 33
AO "	0 93	1 65	0 93	1 69	0 74	1	0 62
UW CMa	0 75	1 83	0 88	2 68	0 60	1	0 84
VV Cep	0 8	1 01	1 00	2 80	(0 50)	1	(1 00)
AH "	0 87	1 75	0 87	3 37	0 70	1	0 68
U CrB	0 38	3 08	0 97	6 70	0 90	6	0 36
Y Cyg	1 00	2 00	1 00	6 10	0 58	2	0 87
GO "	0 85	1 66	0 90	2 66	0 62	2	0 81
MR "	0 85	1 71	1 00	3 30	0 87	2	0 41
YY Gem	0 91	1 89	1 00	5 00	0 56	1	0 90
Z Her	0 81	1 70	1 00	4 88	0 70	4	0 68
RX "	0 86	2 00	0 95	5 23	0 52	4	0 97
TX "	0 88	2 01	1 00	7 18	0 55	4	0 92
u "	0 38	2 11	0 93	3 20	0 67	9	0 73
RT Lac	0 20	2 00	0 93	8 57	0 59	4	0 86
AR "	1 00	2 61	1 00	7 05	0 65	2	0 76
CM "	0 75	1 80	1 00	5 30	0 62	1	0 81
U Oph	0 89	2 11	0 93	4 59	0 60	2	0 84
WZ "	0 96	1 98	1 00	12 1	0 51	1	0 98
AG Per	0 90	1 70	1 00	3 78	0 60	1	0 84
V Pup	0 77	1 91	0 87	2 55	0 60	2	0 84
U Sge	0 30	2 33	1 00	4 57	0 92	4	0 33
W UMa	0 72	1 80	0 82	2 73	0 62	6	0 81
TX "	0 33	2 43	1 00	7 10	0 96	1	0 26
Z Vul	0 44	2 73	0 90	4 54	0 79	5	0 54
RS "	0 31	3 00	0 97	5 00	0.65	6	0 76

ever, it would seem that for most eclipsing binaries the Harvard system represents a more uniform temperature scale than other classifications. The amplitudes (column 4) are given in order to show how accurate are the relative elements. The symbols *pl*, *p*, *v* denote photoelectric, photographic, and visual observations

The column headed $(1 + k)$ in Table I(b) serves the double purpose of showing the relative sizes of the two components, and whether the heavier component is also larger and brighter, if $(1 + k)$ is greater than 2, it means that the heavier component is smaller The third column, *Ell.*, gives the mean value of the radius in an elliptical system according to the formula

$$r = \sqrt[3]{abc}$$

in units of a. The succeeding columns give respectively the relative total brightness of the heavier component, the number of light curves used in obtaining mean values of L and k, and the computed mass ratio, derived from L.

The wide variety in the peculiarities of individual systems, as shown in Tables I(a) and I(b), does not permit of a detailed discussion of single stars at present Such a discussion will be published later It is possible to give here only a few general remarks

The systems S Antliæ and β Aurigæ, though well observed photoelectrically, have such small amplitudes that there is always uncertainty in deducing their absolute dimensions. The ratio of the radii has been adopted after an investigation by the author of all light curves published elsewhere, the ratio for ι Bootis was re-computed. The elements of AO Cassiopeiæ, derived by Pearce, are somewhat doubtful because of uncertainty in the light curve used by him. A new set of photoelectric observations by Bennet at Yale has confirmed the range of the light variation, so that there is little expectation that the absolute dimensions given by Pearce will be much changed; but the uncertainty due to the small range is not wholly removed. The system UW Canis

Majoris is uncertain for the same reason, though probably to a less degree than AO Cassiopeiæ, for the depths of minima in UW Canis Majoris are much greater than those in AO Cassiopeiæ. A new photoelectric light curve would contribute toward more precise values

The mass ratio for VV Cephei, the heaviest of the known eclipsing systems, has not been determined with quite enough certainty, though all results seem to lead to the conclusion that it is not far from the real value Probably a new photoelectric light curve should be obtained for AH Cephei The dimensions of MR Cygni have been derived by the writer on the basis of the relative elements given by Jonson and Kopal WZ Ophiuchi, the most recently discovered eclipsing system, has already been discussed by the writer[9] V Puppis is not yet known spectroscopically with enough certainty The elements for TX Ursæ Majoris have also been derived by the writer[*]

It was said above that there is a correlation between α and L_1 Hypothetically the mass ratio may have any value, but statistically, as seen in Table I, for the majority of the systems the value is much greater than a half Plotting the values of L and α and adopting a linear relation, we find the following formula for computing the mass ratio from the relative total brightness of the heavier component

$$\alpha = 0.20 + 1.6(1 - L_1) \tag{7}$$

A comparison between the computed α_c and the observed values of α given in Table I(*b*) leads to the conclusion that for 21 systems the computed α does not deviate from the observed by more than ten per cent. When we remember that Equation (6) is very insensitive to changes in α, it is permissible to conclude that α may be derived with considerable certainty from the light curve in computing the masses. We should note that some systems, such as u Herculis, RT Lacertæ, and RS Vulpeculæ, show a large positive difference between the computed and the observed α's, whereas RS Canum Venaticorum, AO Cassiopeiæ, and AR Lacertæ show a large negative difference These systems are not entirely well established, but even such large differences do not influence the computed masses very much

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[9] H B 907, 1938

[*] Much has been published in regard to the eclipsing variables Some authors do not agree completely with others in their results, so that there is wide variation (as much as 20 per cent) in the derived absolute dimensions for certain systems In order to eliminate this difficulty we have taken mean values, with proper consideration for the accuracy of the individual light curves

TABLE II

COMPUTED MASSES OF THE HEAVIER COMPONENTS FOR 35 ECLIPSING VARIABLES

Star	Adopted Temp	Computed Mass		Observed Mass	Star	Adopted Temp	Computed Mass		Observed Mass
		$p = 0$ 0	$p = 0$ 2				$p = 0$ 0	$p = 0$ 2	
		⊙	⊙	⊙			⊙	⊙	⊙
S Ant	7800°	1 98	1 88	0 75	YY Gem	3200°	0 31	0 37	0 63
σ Aql	12400	5 81	5 07	6 19	Z Her	7100	2 98	2 74	1 6
TT Aur	18000	9 57	8 05	6 70	RX Her	11000	3 90	3 52	2 2
WW Aur	8500	2 32	2 17	2 20	TX Her	9900	2 70	2 50	2 1
AR Aur	11000	3 93	3 53	2 68	u Her	18000	14 3	11 6	7 52
β Aur	10400	4 07	3 61	2 40	RT Lac	5200	2 70	2 50	5 00
ζ Aur	3300	17 6	14 0	16 4	AR Lac	5400	0 89	0 90	1 42
ι Boo	5700	0 54	0 57	0 64	CM Lac	9100	2 95	2 72	2 07
RS CVn	6700	2 88	2 65	1 85	U Oph	15000	7 12	6 31	5 36
TV Cas	11000	4 38	3 91	1 83	WZ Oph	6000	1 12	1 09	1 41
AO Cas	26000	65 0	47 3	36 3	AG Per	18000	12 0	10 0	5 2
UW CMa	25000	51 4	37 9	40 3	V Pup	21400	22 4	17 6	21 2
VV Cep	2500	48 8	36 3	44 3	U Sge	11700	6 63	5 73	6 70
AH Cep	18000	13 0	10 6	14 6	W UMa	6100	0 88	0 90	0 75
U CrB	15000	6 97	6 00	5 3	TX UMa	11700	4 40	3 90	3 03
Y Cyg	24500	18 8	15 0	17 6	Z Vul	18000	11 3	9 38	5 24
GO Cyg	11700	4 65	4 13	1 04	RS Vul	12400	5 62	4 92	4 6
MR Cyg	11000	5 47	4 80	3 03					

The results for the masses of the heavier components are given in Table II The computed mass, as may be seen from the table, is in better agreement with the observed value for the mass-luminosity relation when $p = 0.2$ than when $p = 0$ 0, especially for large masses. There are three sources of error in the computed masses. First, the error may lie in the temperature scale used in the computation. The scale used here was that given by Russell, Dugan and Stewart.[1] There are other temperature scales which give higher values for a given spectral class, so that a larger discrepancy between the observed and computed masses would result from their use. Secondly, the uncertainty may lie in the systematic error of classification—the spectra may be taken too early. Thirdly, the error may arise from the reflection effect. If we take into consideration all these uncertainties, we may be satisfied with the general accuracy of our results. We may note further that rather uncertain systems, such as ζ Aurigæ, UW Canis Majoris, and VV Cephei show a close agreement, but that such systems as β Aurigæ, TV Cassiopeiæ, u Herculis, and Z Vulpeculæ, for which the values are considered as the best determined, show poor agreement. Either they are not actually the best determined, or the systems are peculiar. GO Cygni is in a special category—the computed mass is more than four times greater than the observed. This is the largest disagreement to be found in Table II. According to the period, the spectrum should be much later, and yet there is no evidence of error in the observational results.

5. Section 4 was concerned with the problems mentioned in Sections 1 and 2. We now proceed to the problem of temperature alluded to in Section 3.

The temperature can be computed by the following formula

$$6 \log T = (7 + 3p)/2 \log m - \log (1 + \alpha) - 2 \log P - 3 \log r - 1.871 \qquad (8)$$

The designations are the same as before (T is in units of the solar temperature = 6000°). Table III gives our results for 70 components of 35 eclipsing systems, computed on the basis of the two values of p indicated. If any other $p = x$ be used, then the following relation would apply.

$$\log T_{p=x} = \log T_{p=0.0} + x/4 \log m.$$

The results in Table III are interesting in two ways. First, such stars as Y Cygni, ι Bootis, and V Puppis, which may be regarded as among the best determined systems, show good agreement. Secondly, there is a tendency for the temperatures of most eclipsing variables to be lower than would be expected from the usual criteria.

TABLE III

TEMPERATURE OF 70 COMPONENTS OF 35 ECLIPSING SYSTEMS

Star	Logarithm of Temperature				Star	Logarithm of Temperature			
	Heavier		Lighter			Heavier		Lighter	
	p = 0 0	p = 0 2	p = 0 0	p = 0 2		p = 0 0	p = 0 2	p = 0 0	p = 0 2
S Ant	3 65	3 66	3 42	3 40	YY Gem	3 68	3 67	3 68	3 67
σ Aql	4 11	4 15	4 04	4 08	Z Her	3 70	3 70	3 66	3 67
TT Aur	4 16	4 21	4 04	4 08	RX “	3 86	3 89	3 86	3 87
WW “	3 90	3 91	3 86	3 87	TX “	3 92	3 94	3 83	3 84
AR “	3 95	3 97	3 91	3 93	u “	4 09	4 13	3 80	3 82
β “	3 88	3 91	3 83	3 85	RT Lac	3 87	3 90	3 44	3 44
ζ “	3 50	3 54	4 13	4 18	CM “	3 90	3 91	3 72	3 73
i Boo	3 73	3 71	3 74	3 73	AR “	3 86	3 87	3 65	3 66
RS CVn	3 72	3 73	3 56	3 57	U Oph	4 14	4 18	4 03	4 06
TV Cas	3 82	3 83	3 54	3 55	WZ “	3 83	3 85	3 83	3 85
AO “	4 27	4 34	4 33	4 41	AG Per	4 04	4 08	4 10	4 12
UW CMa	4 33	4 41	4 32	4 39	V Pup	4 35	4 41	4 16	4 19
VV Cep	3 34	3 44	4 24	4 32	U Sge	4 10	4 11	3 67	3 68
AH “	4 30	4 35	4 30	4 36	W UMa	3 75	3 75	3 64	3 63
U CrB	4 11	4 14	3 61	3 63	TX “	4 02	4 05	3 20	3 20
Y Cyg	4 38	4 44	4 38	4 44	Z Vul	4 04	4 08	3 82	3 83
GO “	3 64	3 69	3 72	3 73	RS Val	3 97	4 01	3 49	3 50
MR “	3 89	3 91	3 91	3 93					

Since the spread of temperature for a given spectral class, especially for stars later than Class A, is large, we can deduce two temperature limits in agreement with Table III. The results are given in Table IV. The low character of the temperatures is partly established through two supergiants, ζ Aurigæ and VV Cephei, the rest of the contributors are not

TABLE IV

THE DEDUCED TEMPERATURE SCALE FROM 70 ECLIPSING COMPONENTS

Spectrum	Temperature	Spectrum	Temperature	Spectrum	Temperature
O7	28000°	F5	6300° high	K0	4600° high
B0	21000		3300 low		3800 medium
B5	14700	G0	5750 high		2700 low
A0	10000		3000 low	K5	4000 high
A5	8400	G5	5100 high		3300 medium
A8	7900 high		4200 medium		2500 low
	6600 low		2900 low	Me	3400 high
F0	7400 high				3000 medium
	6200 low				2350 low

supergiants in respect to mass and luminosity, although they are much less dense than the sun Even if the existence of such low temperatures is somewhat contrary to expectation, it is difficult to escape from the conclusion that they are probably in the neighborhood of eclipsing-variable temperatures We may add that there are not many, if any, methods which give reliable results for temperatures of the type discussed here, and that deviation from black-body radiation for eclipsing variables may have a much more pronounced effect than has been found for δ Cephei variables

6. There are several eclipsing systems which are unusual in certain respects, and the method of determining absolute dimensions outlined in the previous pages may be of some use in interpreting them.

TABLE V

Star	Period d	L_h	α_c	r_h	r_f	Sp_h	Sp_f	Remarks
ε Aur	9890	0 52	0 72	0 03	0 30	F5p	—	1
SX Cas	36 6	0 54	0 94	0 25	0 52	A6	G6	2
α CrB	17 4	1 00	0 20	0 05	0 02	AO	—	3
W Cru	198 5	0 90	0 36	0 61	0 34	GO	GO	4
GG Car	62 1	0 50	1 00	0 35	0 35	P Cyg	P Cyg	5
β Lyr	12 92	0 63	0 79	0 26	0 62	B8	B5	6
δ Ori	5 73	0 75	0 60	0 38	0 24	B1	—	7
β Per	2 87	0 92	0 34	0 21	0 24	B8	—	8
V 381 Sco	6475	0 97	0 25	0 21	0 42	F5?	—	9
V 383 Sco	4900	0 75	0 60	0 20	0 40	M?	—	10
RY Sct	11 12	0 60	0 84	0 34	0 34	Bq	Bq	11
λ Tau	3 95	0 85	0 44	0 27	0 27	B3	—	12
+ 6° 1309	14 4	0 55	0 92	0 30	0 30	O8	O8	13
+57° 28	55 9	0 70	0 68	0 20	0 27	B9	B5	14
−66° 3307	605	0 85	0 44	0 20	0 27	P Cyg	P Cyg	15

REMARKS

1. Elements taken partly from Güssow's paper (*Veröff. Ber Bab.*, 11, Pt. 3, 1936).

2. Elements taken from Dugan's work (Princeton Cont., No. 13, 1933).

3, 4, 6, 7, 8, 12 Elements taken from a compilation by the writer (*Veröff. Ber. Bab.*, 9, Pt. 5, 1932) where all references are given In addition, see the paper by D. J. K. O'Connell (Publ. Riverview College Obs , No. 3, 1936) on W Crucis.

5. Elements adopted as arbitrary.

9, 10 Miss Swope's stars (H B. 902, 1936), the elements of V 383 Scorpii are arbitrary

11 See Harvard Tercentenary Papers, No. 27, 1937. The system has the spectrum of a nebula.

TABLE VI

THE ABSOLUTE DIMENSIONS OF FIFTEEN INTERESTING BINARIES

Star	Masses		Radii		Distance Between the Centers	Temperature of the Fainter Component
ε Aur	29 2○	21 0○	213○	2130○	7100○	1180°
SX Cas	13 7	12 7	35	75	138	5430
α CrB	3 24	0 7	2 3	0 6	46	3980
W Cru	34 1	12 2	313	158	513	3390
GG Car	58 2	58 2	111	111	317	14800
β Lyr	14 1	11 2	17	40	67	6300
δ Ori	36 2	16 7	19	12	47	16200
ζ Per	5 0	1 7	3 3	4 0	16	2250
V 381 Sco	104	26	1550	3100	7400	1460
V 383 Sco	20 4	12 2	760	1520	3800	1050
RY Sct	22 2	18 6	24	24	72	13000
λ Tau	14 6	6 6	8 0	8 0	29	9670
+ 6° 1309	59 0	54 3	36	36	120	24200
+57° 28	21 4	14 7	43	57	215	6920
−66° 3307	113	49 7	326	435	1630	6400

13, 14 Plaskett's and Pearce's stars respectively. The relative elements are arbitrary, and may be regarded as maximum values

15. Mrs Mayall's star (Harvard Tercentenary Papers, No. 25, 1937) The relative elements are arbitrary, and may be regarded as maximum values

We may point out that the relative elements given in Table V are good average values for eclipsing variables in general, so that one should not expect unusual results. From the relative elements given in Table V we obtain the data of Table VI, which contains the absolute dimensions of the systems considered here.

Concerning the masses, we see from Table VI that the most massive system studied is $-66°\ 3307$, and that the next massive is V_{381} Scorpii It is somewhat surprising that the most massive binaries hitherto found, $+6°\ 1309$ and $+57°\ 28$, here appear to be of relatively low mass, and that the computed masses for these systems are much less than those observed spectroscopically, approximately in the ratio one to four. If we should try to transform the ratio into one to one, attributing the difference wholly to the difference in temperature, then we would have to assume that the effective temperature for Class B9 is over 30,000°. We may add further that for these systems we have assumed the most favorable (maximum) values of the relative elements, and that the observed values are minima, so that if more probable values for the relative elements were adopted the above mentioned large difference would be even greater The system $-66°\ 3307$ is a P Cygni star and hence the usual conception of a continuous decrease in density and effective temperature seems to have little application here, that is, a P Cygni star (others perhaps also) has a "shell-like" structure The same remarks are fully applicable to GG Carinæ The systems α Coronæ Borealis, β Persei, and λ Tauri are not peculiar in absolute dimensions, indeed the values obtained here are in close agreement with those obtained originally by Stebbins, Eddington, and Slavenas The system SX Cassiopeiæ is unusual in that, as a small value of the mass function was found spectroscopically ($f_2 = 0.48$), one would expect a rather low mass. We may here call to mind that this system shows bright lines of hydrogen in its spectrum.

Concerning sizes, V_{381} Scorpii seems to surpass all eclipsing variables in voluminal dimensions, though such systems as VV Cephei (radius $= 2400\odot$, see H.C. 421), ε Aurigæ, and V_{383} Scorpii nearly approach it in size.

Finally, concerning the temperature, we see that the lighter component of the system V_{383} Scorpii seems to have the lowest temperature (1050), though of the same order as the temperature of the lighter component in ε Aurigæ and in

V_{381} Scorpii Especially interesting is the system β Lyræ Spectroscopically it is one of the heaviest systems, the mass function being over eight solar units Spectroscopically also there is a second spectrum, originally called Class B5, which does not show an oscillation reflecting that of the B8 spectrum. Besides, there are bright bands, with absorption wings flanking them All three types of spectra display very little correlation in their behavior, at least in an evident manner, so that several conclusions (Miss Maury, Curtiss, Baxandall, Struve) have been drawn about the existence of a large envelope around the system The low temperature obtained here suggests that the second component must be of a much later spectral class than B5, probably F From this result one is led to conclude that the visible spectrum of B5 character does not come from the second component We should point out here that the computed mass of this system is much lower than would follow from the mass function. The spectrum of the first component must therefore be slightly earlier than B8

SUMMARY

A method has been outlined which allows for determination of the absolute dimensions of an eclipsing system, if the spectrum, period, and relative dimensions, derived from the light curve, are known (Formula (6)) Thirty-five eclipsing systems with known absolute dimensions have been used to obtain a temperature scale (Table IV) Fifteen interesting eclipsing variables, for which no determinations of absolute dimensions have previously existed, have been investigated (Section 6). It has been found that there are four systems in which the fainter component has a radius of over 1000 solar radii (V_{381} Scorpii, 3100, VV Cephei, 2400, ϵ Aurigæ, 2130, and V_{383} Scorpii, 1520), and that there are several faint components with temperatures less than 1500° absolute β Lyræ, Plaskett's, Pearce's, and Mrs. Mayall's stars have been taken into consideration.

I am grateful for the opportunity of discussing the above results with Dr M. Schwarzschild.

WITH AN ASTRONOMER ON AN ECLIPSE EXPEDITION *

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Abstract

From eclipse expeditions in comparatively recent years there have been two outstanding achievements The first was the verification of the Einstein general theory of relativity by the measurement of the deflection of the light from stars by the strong gravitational attraction of the sun The Einstein theory not only has had important consequences for the physical sciences but also started a new trend of philosophical thought The second result from eclipse expeditions has been the measurement of the heights in kilometers to which gases extend in the sun's atmosphere, the chromosphere Coupled with great advances in knowledge of the structure of the atom, these heights gave to Saha the confirmation of his theory of ionization The past two decades have, in consequence, been the most exciting and the most prolific years in the whole history of astronomy

All the prominent lines in the solar spectrum have been assigned to multiplet groups with known excitation potentials measured in electron-volts from which have been ascertained the relative numbers of atoms engaged in the formation of the spectrum lines Coupled with heights derived from eclipse spectra, the Evershed displacement in sun-spots has shown that there is a circulation of gaseous material near the sun's surface proving that each sun-spot is a gigantic vortex The red shift from the Einstein theory is confirmed in the sun but the heights from eclipse spectra show that the strong lines, those of low excitation potentials extending to the greatest heights, in addition to the relativity shift show a motion of descent towards the sun while the weak lines of high excitation potentials which extend only to small heights have a motion of ascent Within a strong multiplet group, there are important correlations with the result that the heights found directly from the flash spectrum or from the Evershed effect are not constant but are the greatest for the lines of greatest intensity which involve the largest number of atoms A knowledge of heights also gives knowledge of the density distribution of various elements in the lower chromosphere, together with an indication that turbulence and not selective radiation pressure is responsible for keeping the different elements so well mixed

Solar eclipse observers must always be confirmed optimists and good philosophers, or in other words, they must be willing to gamble at long odds on eclipse day with the fickle weather. Some astronomers have had a long run of bad luck For instance, in 1936 in Japan, the sky at the time of the eclipse had been perfectly clear right up to the time of totality and then it suddenly clouded up. Similar conditions had

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* The Penrose Memorial Lecture delivered April 22, 1938

been met previously by three members of the British expedition with the result that in a total of twelve attempts to observe an eclipse there had been only one success. On the other hand, some members of the American Philosophical Society, notably W. W. Campbell and John A. Miller, at some eclipses have had remarkably close shaves from clouds, but miracles seem to have happened and when all hope was gone the skies suddenly cleared off for just a few moments at totality and then clouded up again for the rest of the day In the observation of eclipses, I too have had a generous share of good luck

In the article entitled "Nature's Most Dramatic Spectacle," [1] is given a popular account of the National Geographic Society-U S Navy expedition to Canton Island in mid-Pacific Ocean to observe the total eclipse of June 8, 1937 U S S "Avocet" carried the thirteen members of the expedition and the equipment consisting of 150 cases of instruments, ten thousand board feet of lumber, sixty bags of cement, tents, cots and supplies for a six weeks' trip away from the base at Honolulu

The scientific program carried out by the expedition consisted of the following

Captain J F. Hellweg, U S. N. (retired), superintendent of the U S Naval Observatory, gave the signals for the four contacts and counted time

S A Mitchell, University of Virginia, had three concave grating spectrographs, each used without slit, for photographing the spectrum of the chromosphere and the corona

F K. Richtmyer, Cornell University, had four identical lenses for photographing the corona, with three of which he had screens of "polaroid" rotated at different angles. The purpose was to measure the polarization in the corona. With illumination meters and a photoelectric cell, he measured the intensity of illumination during the progress of the eclipse from first to fourth contact and also the total light of the corona compared to that of the full moon.

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[1] *National Geographic Magazine*, 72, 361, 1937

Theodore Dunham, Jr, Mount Wilson Observatory and Charles G Thompson, president of the Foundation for Astrophysical Research, New York, used a powerful spectrograph which was virtually a duplicate of that on the 100-inch Mt. Wilson reflecting telescope

Irvine C. Gardner, National Bureau of Standards, Washington, D. C, photographed the corona in black and white and in colors by using a camera constructed under his direction of 9 inches aperture and 19 feet focal length

Paul A McNally, S J, Georgetown University Observatory, photographed the corona through different color-filters and with plates specially sensitive to different spectral regions

John E Willis, U S Naval Observatory, photographed the partial phases of the eclipse and also the corona with a 6-inch aperture and 15-foot focus camera

Charles Bittinger, Washington, painted the corona on a canvas 60 x 60 inches. The painting was on exhibit during the reception following the Penrose Memorial lecture

R H. Stewart, National Geographic Society, assisted Dr Gardner during the total eclipse and also obtained a moving picture film of the eclipsed sun from first through to fourth contact

In addition, the National Broadcasting Company had an announcer (George Hicks) and two engineers, Brown and Adams.

This was my fourth cruise on eclipse expeditions with the United States Navy, the three previous ones having been to Sumatra in 1901, Spain in 1905 and Niuafoou Island in 1930. Twice before I had been across the equator and had paid proper homage to Father Neptune so that in 1937 I was no longer a land lubber.

This 1937 eclipse will be memorable for four different reasons. first, for the longest duration of totality of any eclipse in more than twelve hundred years (since the year 699), second, that it began on June 9 and ended on June 8, the day before it started, third, in spite of being in the tropics where clouds are the rule rather than the exception, the skies were clear at each and every station where there was an expedition, and fourth, in spite of isolation and long distances, interested persons could listen in on frequent broadcasts that told of the life on the island and of the progress of preparations over a coast-to-coast network. Two of the broadcasts were specially dramatic, one of fifteen minutes duration with totality at the middle of it, which gave a graphic description of the spectacular phenomenon, the other a few hours later when I, as the scientific leader of the expedition from Canton Island, held a broadcasted conversation with London half way round the world In the great metropolis was a friend of many years standing, Alfred Fowler, a distinguished astronomer who in 1893 had made the first photograph of the flash spectrum, which since the year 1900 has been my own chief interest at eclipses

On May 26, the party from New Zealand arrived aboard H M S "Wellington" There were eight in the expedition, two of whom had worked alongside me on Niuafoou or "Tin-Can" Island at the eclipse of October 21, 1930 It was pleasant to renew old friendships.

Ashore we kept Honolulu time and we had an hour of daylight saving As we were near the equator (3° South), the sun actually rose near six o'clock, but as our clocks said seven o'clock, everybody got up without grumbling and went to work immediately after breakfast

On eclipse day we were awakened by a loud-lunged sailor at 4 40 A M , though some members of the expedition had not been able to go to bed at all on account of last minute preparations. The skies had been clear the night before until after midnight It was hopelessly cloudy when we emerged from our tents about five o'clock. There was a broadcast at 5 30 A M , at which time we gave impressions of the weather at earlier eclipses observed and gave expression to our hopes and expectations for clear skies A hurried breakfast was at six o'clock under the light of lanterns, with the clouds somewhat broken but still bad towards the point of sunrise At sunrise, conditions were greatly improved We did not have long to wait to find what our luck was going to be for the reason that a quarter of an hour later the whole sky was clear except for floating clouds here and there We were in rare good luck for the only clouds over the sun from first contact at 7 35, through to fourth contact more that two hours later, were a few thin ones, the first of which passed over the sun about three minutes after the precious photographs had all been taken during totality

In the present article, attention will be confined to scientific discoveries made from eclipse expeditions in recent years and an attempt will be made to formulate the outstanding problems that await solution at eclipses in the years to come In the James Arthur lecture delivered at the Smithsonian Institution in February, 1937 and published in the Smithsonian Annual Report, greater details are given for various phases of the work

To the naked eye, the 1937 corona was circular in outline to an angular distance of one solar diameter In addition there were many long spikes going out at various angles, the longest being two diameters in length Looking through a hollow tube to protect the eye from sky illumination, a New Zealand observer on Canton Island saw one streamer extending to four solar diameters while a photograph taken by F K Richtmyer showed a spike extending to six diameters From Peru, at an elevation of 25,000 feet, but on account of the low altitude of the eclipsed sun, with an air-mass three times that of a zenith sun at sea-level, Major Stevens obtained airplane photographs showing a "globular corona" extending to one solar diameter At greater angular distances the long pointed streamers made a gorgeous spectacle, perhaps the most beautiful of my ten total eclipses Although all the developed photographs showed many prominences, there were no huge masses such as occurred at the eclipses of 1918 and 1919, with consequent disappointment to those observers who were photographing the corona by color processes. On Canton Island, Gardner used three different methods. The developed photographs showed a greener corona than was visible to the eye. Gardner and also Michie of New Zealand used a rotating sector to cut down the brightness of the inner corona, a method which was tried first in 1889 The 1937 results were none too satisfactory

The corona may be photographed by cameras large and small, fast or slow. With cameras of great length it is necessary to counteract the diurnal motion. This may be done by mounting the telescope horizontally and then using a plane coelostat mirror or by pointing the object glass directly to the sun. For moderate focal lengths up to 15 feet, a polar axis may be employed but for greater lengths a tower telescope is erected The Swarthmore astronomers have obtained exquisite definition with focal lengths of 65 feet

It is interesting to note that at eclipse expeditions success has always been greater in the direct photography of the corona than in any other branch of the investigation. The reason is evident, namely, that in every well-equipped expedition, no matter what the other program may be, the corona is always photographed However, there is another reason not so apparent, which is that perfection of focus and conditions of "seeing," although desirable, are not absolutely essential in obtaining successful photographs of coronal details A lack of perfect focus plays havoc with spectroscopic photographs but detracts little from the beauty of the coronal images for the reason that its structure is always nebulous or filmy in detail

The general shape of the corona can be predicted[2] in advance of the eclipse depending on the sun-spot cycle. Recently it has been found that the "minimum type" of corona, with long equatorial streamers and stong polar brushes does not occur at the time of minimum of spots but 1.25 years earlier. Likewise, the corona closest in shape to a circle takes place 1 25 years before spot maximum The eclipse of 1932 took place 1 2 years before minimum of spots and its shape was the pronounced elongated type The succeeding total eclipse of 1934 was only 0.2 years after spot minimum and yet the corona had lost its minimum-type features and much more closely resembled the circular or "maximum-type" corona. Although the time of next sunspot maximum is still uncertain, it is highly probable that the eclipse of 1937 occurred within a year in advance of maximum Its shape, almost exactly circular was the one confidently predicted

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[2] *Handbuch der Astrophysik*, 7, 396, 1936.

Many attempts have been made to detect motions of coronal materials but without pronounced success A comparison of Swarthmore and Lick photographs of the 1918 eclipse seemed to indicate motions of the order of 10 miles per second, but at the 1926 eclipse a comparison of coronal photographs [3] made in East Africa and Sumatra revealed that any motions in the corona were no more than one mile per second, or no greater that the inherent errors of measurement. The few spectroscopic measures that have been made seem to indicate motions away from the sun at speeds of 15 miles per second, though the evidence is not very convincing and needs to be verified

Valuable information [4] regarding details of coronal radiation were secured in 1930 from large scale spectra taken with a concave grating without slit when the coronal lines are rings of light and not the customary straight lines one expects in spectra. The spectrograms were compared with direct photographs of exquisite detail in the corona and also with spectroheliograms taken on four successive days thousands of miles away at Mt Wilson or Kodaikanal Observatories. All of the photographs tell of an intimate connection between coronal streamers and prominences but also that the streamers, on which the shape of the corona more or less depends, are always located near prominences but are not necessarily exactly connected with those prominences which at the time of the eclipse are of the greatest height. The eclipse spectra showed that the details of the coronal structure in the green "coronium" line at 5303 A differed greatly from the details found in the red line at 6374 A

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[3] Ibid, 399

[4] *Astrophysical Journal*, *75*, 1, 1932

In the report of the Commission on Eclipses presented to the International Astronomical Union at the Paris meeting in 1935, it seemed that we might be on the verge of a fairly complete understanding of the method whereby the light of the corona is diffused and scattered. Grotrian had found that the distribution of energy in the spectrum of the corona is identical with that in the solar spectrum, the dark lines in the spectrum of the outer corona giving fair indication that the light of the corona is scattered sunlight At the 1932 eclipse, Dufay and Grouiller had shown that the amount of polarization in the corona is entirely independent of wave-length and is a maximum of 26 per cent at an angular distance 10′ from the sun's limb

Other observers, however, have come to quite different conclusions From the two eclipses of 1932 and 1934, Cohn[6] finds that the polarization in the corona is quite different for short and for long wave-lengths In fact, the polarization in the integrated light, in the blue and in the red increases steadily from the sun's limb toward the outer corona, whereas it reaches maxima both in the violet and in the green and then decreases again. At 4.5′ from the sun's limb the polarization is actually independent of wave-length but at smaller distances in the inner corona the polarization is higher for short wave-lengths than for long wave-lengths. At the 1936 eclipse Zakharin confirms the conclusions of Cohn that the degree of polarization is different for different regions of the spectrum.

Likewise our knowledge regarding the law of distribution of light within the corona is in a very unsatisfactory state. There are many laws of intensity found by various observers, such as the 2nd, 3rd, 6th, 7th, 8th and such powers as 2.3 or 2.4 of the distance measured either from the center or from the edge of the sun. At the 1936 eclipse, the Polish expedition found that the intensity of the coronal radiation measured from the sun's limb outward diminishes more rapidly in red light than in yellow while the Italian photographs at the same eclipse showed that the intensity in the blue also diminished more rapidly than in the yellow On the contrary at the same eclipse, the Japanese expedition [6] finds that the coronal light diminishes in intensity inversely as the 3 5 power in blue light and as the 5 5 power in yellow light, the distances outward being measured from the sun's center.

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[6] Ibid, 87, 284, 1938.

In view of much conflicting evidence it is very important that measures both of intensity and of polarization be repeated in different wave-lengths by many different observers. For polarization measures there has come a great simplicity of technique through the application of "polaroid" to eclipse work, which has been done both at the 1936 and 1937 eclipses

Accurate values of the total light of the corona have been derived by Richtmyer and by Stebbins [7] in Peru, each using a photoelectric cell. The two results are in good agreement, namely, 53 and 47 per cent, respectively of the total light of full moon At the eclipses of 1918 and 1925, the photoelectric cell used by Kunz and Stebbins gave values of 50 and 44 per cent, respectively From the ten most reliable measures previous to 1937, the average showed the total coronal light 47 per cent of the full moon.

Measures by illumination meters of the intensity of light of the corona plus illuminated sky have given much conflicting information for the reason that it has been impossible to allow adequately for the effects of sky illumination. In spite of the conflicting evidence, however, some astronomers have reached too hasty conclusions in their attempts to correlate intensity of coronal radiation with sun-spot activity. It does indeed seem probable that the inner corona at spot maximum must be brighter than at spot minimum. Moreover, as the inner corona contributes the greatest part of the energy of the total coronal radiation, we would logically expect that the total energy at maximum of spots would be greater that at minimum. Unfortunately, eclipses come but seldom and there are far too few observations from which to derive any satisfactory correlations.

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[6] *Ann Tokyo Obs*, 2nd Ser, *1*, 91 and 139, 1938

[7] *Astrophysical Journal*, *87*, 225, 1938.

In spite of many inconsistencies in the results, observers throughout the past fifty years have been in substantial agreement that the total light of the corona is roughly one-half that of the full moon, or one-millionth that of noon-day sun.

In the year 1882 a bright comet was observed near the eclipsed sun but was never seen before nor since. The corona appeared so bright that attempts were made to photograph it without waiting for an eclipse. Attempts followed attempts with every conceivable variety of attack—and failure to achieve results followed failure for nearly fifty years. In fact, it was not until 1930 that Lyot of the Meudon Observatory achieved a brilliant success where others had repeated failures. His great triumph resulted from the ingenious arrangement of his telescope to reduce to a minimum the amount of scattered light inside the instrument. A mountain observatory on the Pic du Midi (9100 feet) and skies at times very transparent permitted photographs of the brighter parts of the corona in full daylight but he also derived wave lengths of the emission lines of "coronium." Following his earlier successes, Lyot[8] has determined from the mountain observatory during the past three summers the wave-lengths of eleven lines with the following values and probable errors:

3388.10 ± .07
5116.03 ± .02
5302.86 ± .02
5694.42 ± .07
6374.51 ± .03
6701.83 ± .03
7059.62 ± .05
7891.94 ± .07
8024.21 ± .10
10746.80 ± .15
10797.95 ± .15

The three last lines have not yet been photographed at eclipses. In the summer of 1937 Lyot obtained 125 spectra.

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[8] *C. R.*, *202*, 392 and 1259, *203*, 1327, 1936 and *C. R.* 1938 (in advance of publication).

The line 5694 A was discovered this past year. It is faint but it appears with a dispersion of 7 5 A per mm It is fainter than 5116 A which in turn was not seen in 1935 but was photographed both in 1936 and 1937. Lyot has not yet photographed the coronal line 5536 A which has been observed several times in the past thirty years with an intensity about equal to 5116 A Lyot reports that the intensities of the coronal lines vary, the line 6702 A was stronger in 1937 than in 1936 and it was more intense than 7059 A. The line in the infra-red at 8024 A is generally quite feeble but it appears on several spectra taken under good conditions

Lyot was the first to find that the green and red coronium lines 5303 and 6374 are broad lines Later measures give the equivalent widths of 5303, 6374 and 6702 to be 0 80,0 97 and 1.07 A, respectively, the quotient of the equivalent width by the wave-length being very nearly a constant He has also succeeded in the remarkable feat of photographing the 5303 line near sea-level at the Meudon Observatory

The coronal line 7892 A was discovered by Curtis and Burns in 1925 It was photographed at the 1936 eclipse by Williams and in 1937 by Mitchell using the same spectrograph that was employed in its discovery in 1925 It is a strong line, in fact, it has a greater absolute intensity than 6374 A

In addition to the eleven lines measured by Lyot, there are twelve other lines in the spectrum [9] of the corona that have been observed at many eclipses. Consequently, there are 23 known emission lines. In addition, at the 1936 eclipse two Japanese expeditions publish a total of 11 lines in the region between 5000 and 7000 A where Lyot's spectra were photographed under the best conditions These lines are faint and need to be verified by future observations

It may be said that the corona exhibits three separate spectra: first, the emission spectrum in the inner corona extending to 5′ or 200,000 km from the sun's edge, second, the continuous spectrum (without lines) in the middle corona; and third, the Fraunhofer lines showing feebly in the outer corona In the continuous spectrum it has been found [10] that there is a band of absorption at wave-length about 6300 A which has a greater intensity in the corona than in the photosphere At the same eclipse, this band was photographed [11] in the spectrum of the light of sky during totality The same band appears in the spectrum of twilight, in the spectrum of the night sky and also in the spectrum [12] of the aurora borealis In accordance with the theory of Stormer that aurorae are caused by corpuscular radiation from the sun, then it must happen that at the time of intense solar activity there would be a strong aurora on the side of the earth turned towards the sun The band seen in the 1936 spectra needs to be confirmed at future eclipses but it does look probable that it is actually the auroral band which one would expect to be strong near the time of sun-spot maximum.

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[9] S A. Mitchell, *Eclipses of the Sun*, p 376, 1935.

By comparing wave-lengths east and west, Lyot [8] finds, that the inner corona rotates at a speed about equal to that of the photosphere.

In comparing the green and red coronal rings obtained [4] in 1930 on spectra taken with a concave grating and without slit, it was surprising to find how little the lines resembled each other in their structural details or how little either resembled the H and K lines in the chromosphere It is evident that these two lines cannot take their origin in the same atom, or at least, not in the same atom in the same state of ionization In spite of many attempts, no further progress has been made in deciphering the source of coronium.

In the elucidation of the enigmas of the corona much substantial progress has been made but yet there are many unsolved problems. According to Rosseland, "the corona has stimulated speculation to the breaking point, it being even suggested that there we witness our recognized physical laws set at naught by nature itself." It is evident that the cause of the coronal radiation cannot be found in the emission spectrum of coronium which contributes only a very small fraction to the total energy of coronal light We must therefor seek the explanation of the mysterious corona in the spectrum of the middle and outer corona

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[10] *Proc Phys Math Japan*, *19*, 693, 1937

[11] *Mem Czech Astr Assn*, No 5, 1937

[12] *Nature*, *139*, 584, 1937

As the result of many different theories, it is now generally recognized that the electron[13] must play an important role in explaining the radiation of the corona If the continuous spectrum is caused by free electrons, then the average thermal velocity of the electron would cause a Doppler effect of the order of ten angstroms which would effectually wipe out all Fraunhofer lines with the exception of the broad wings of the H and K lines Electron scattering will give an adequate explanation of the absence of dark lines in the inner corona and also is in conformity with the fact that there is little difference in energy distribution between the radiation of the corona and that of scattered sunlight

Although substantial progress has been made there are important problems connected with the corona that await solution In future eclipses there is a great need of carefully designed spectrographs of great speed and large dispersion At the 1937 eclipse, Dunham had the most powerful spectrograph ever used at an eclipse for the chromosphere and for the corona With smaller dispersions we need to compare the intensity distribution of coronal light with that of the photosphere and we need more and better spectra that will give the dark lines in the outer coronal spectrum that should be taken under clear skies devoid of water vapor in order that the photographs may verify that the Fraunhofer lines are coronal in origin and do not come from sunlight scattered in the earth's atmosphere

Lyot has contributed much valuable information to the emission spectrum of coronium but the outstanding problems connected with the corona will be solved only by observations made at total eclipses The chief difficulty is that on the average only one minute per year is given to any astronomer to secure his important observations. The next total eclipse to be observed will be on October 1, 1940, visible in Brazil and South Africa.

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[13] *Handbuch der Astrophysik*, 7, 404, 1936

In recent years the chief contributions from observations made during total eclipses of the sun have had no connection with the *corona* but have been *in two* widely separated fields of investigation In 1919, at the eclipse which was the forerunner in the Saros cycle of the eclipse of June 8, 1937, the whole world was electrified by the confirmation of the Einstein prediction that rays from stars are bent when under the influence of the strong gravitational pull of the sun Although the splendid observations at the 1922 eclipse seemed to give a complete verification [14] of the Einstein value, it was found by Freundlich from observations at the 1929 eclipse that the deflection at the sun's limb was considerably greater than 1 75″ required by theory and amounted to 2 24″. The chief trouble with eclipse plates is that the same stars which furnish the relativity displacements must also give the scale of the photographs. The stars at the 1929 eclipse were badly distributed around the sun as is seen by the fact that out of a total of 18 stars used to measure the relativity effect there were 17 stars located on one side of the sun and only one star on the other side, with the result that scale value was poorly determined A discussion by Trumpler of all observations at the eclipses of 1919, 1922 and 1929 gives the relativity deflection reduced to the sun's edge as 1.79″ ± 0 06″

In view of the discordant results from the 1929 eclipse, it is evidently necessary to repeat the observations, devoting special care to a more accurate determination of the scale value of the photographs. Unfortunately, this obvious recommendation can hardly be put into effect for the reason that the star fields at total eclipses in the next twenty years do not contain a sufficient number of bright stars.' In spite of these drawbacks, the British astronomers are planning to test again the Einstein deflection as a part of a very extensive program of observations for the 1940 eclipse.

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[14] Ibid , p 408

The sun is the nearest of the fixed stars and it is the only star which permits a detailed study of conditions in the outlying atmosphere. As these conditions have gradually become understood in the sun they have furnished the method of interpreting many outstanding stellar problems The greatest contribution in recent years from eclipse observations has been the rather perfect knowledge of heights to which the gases of the chromosphere extend above the surface of the sun. Photographs of the flash spectrum taken without a slit give a spectrum of curved arcs from which heights are immediately derived. From these heights furnished to Saha fifteen years ago he was able to compute the conditions of temperature and reduced pressure that cause an atom to lose an external electron and become ionized His theory of ionization coupled with increased knowledge of the structure of the atom has made the past fifteen years the most prolific and most exciting years in the whole history of astronomy.

All the prominent lines in the spectrum of the sun have been assigned to multiplet groups with known excitation potentials measured in electron-volts, the arbritary intensity scale of Rowland has been submitted to calibration tests which have revealed that the intensities depend on the numbers of atoms engaged in the formation of the spectral lines. From the weakest iron lines perceptible in the solar spectrum to the strongest the number of atoms involved increases about one million times

A person with no knowledge of the theory underlying multiplet groups would not advance very far in the practical operation of correlating heights from eclipse spectra with intensities before the fact would be forced upon his attention that the lines of greatest intensities generally reach the greatest heights, and moreover for any element considered, the intensities and heights are greatest for lines of lowest excitation potential.

Fascinating work on sun-spots was started [15] by Evershed and carried through to completion by St. John using the 150-

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[15] *Eclipses of the Sun*, p 340

foot tower telescope of Mt Wilson With the slit of the spectrograph placed across the image of a spot it was found that the wave-lengths in the penumbra of the spots were different from the values at the center of the sun These "Evershed displacements," as they are called affected practically all lines but the amount depended on the intensities of the lines The heights derived from eclipse spectra furnished the explanation The layers closest to the sun's surface have a motion of translation out of the spot at the rate of 2 km per sec At greater and greater heights this motion becomes less and less

At a certain level the outward motion of vapors ceases and at still greater heights the motion of translation is in the opposite direction into the spot At the maximum heights reached by the H and K lines of ionized calcium, the speed of motion into the spot is 3 8 km. per sec

The Evershed effect shows that there is a circulation of gaseous material in the neighborhood of sun-spots, or in other words, that each sun-spot is a great vortex

One consequence of the Einstein theory of relativity is that wave-lengths in the sun must be greater than in the laboratory, the amount of shift to the red depending on the wave-length The best element for determining the red shift [16] in the sun is iron. From the discussion of abundant material together with heights derived from eclipse spectra, it is evident that the relativity shift is most certainly present, but in addition there are systematic differences between the effects shown by the strong and the weak iron lines, the strong lines being those that extend to the greater heights in the sun The systematic differences are most readily explained as a Doppler shift caused by a circulation of vapors in the sun's atmosphere On account on the higher temperatures and higher pressures near the photosphere, the solar activity causes the Fe atoms to ascend through the medium of thousands of weak lines of high excitation potentials. In the upper reaches of the chromosphere under reduced pressures some of the atoms lose an external electron and become ionized. Later the atoms descend from their maximum heights and in their descent some of the atoms gain an external electron and again become neutral. According to this interpretation, in a direct photograph of the sun showing a mottled surface, the atoms ascending exhibit themselves over the small bright granules and the descending ones over the larger dark interspaces, the observed effect being an integrated one

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[16] Ibid, p 416

In the celestial laboratory in the sun the astronomer has available for his researches very high temperatures and very minute pressures far transcending the conditions available to the physicist in terrestrial laboratories As the result of a knowledge of the structure of the atom, Henry Norris Russell and others have assigned practically all the strong lines in the solar spectrum to multiplet groups and have ascertained the energy, measured in electron-volts, necessary to produce the spectral lines From a knowledge of the multiplet intensity formulae it has been possible to learn the relative numbers of atoms involved in the transfer from one energy level to another in the production of absorption or emission in the sun's atmosphere

The heights determined from eclipse spectra to which the solar gases extend in the chromosphere have permitted many other important correlations These correlations are shown by the dozen lines of a multiplet involving[17] strong Fe lines, where 100 times as many atoms are active in producing the strongest line in the multiplet at wave-length 3820 A as go to form the weakest line at 3940 A. Even within a single multiplet, the heights found directly from the flash spectrum or from the Evershed effect in sun-spots, are not constant in amount but the heights are greatest for the lines of greatest intensities which involve the largest number of atoms

Again, a knowledge of the heights from the flash spectrum to which the various lines in multiplets are observed combined with information from the number of atoms involved gives important knowledge [18] regarding the density distribution of various elements in the lower chromosphere. The results seem to indicate that turbulance and not selective radiation pressure is responsible for keeping the different elements so well mixed.

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[17] Ibid, p 348

From the flash spectrum there has been determined [18] the relative abundances of various elements and the results from the chromosphere have been compared with the abundances found in the sun's reversing layer, in stellar atmospheres, in the earth's crust and in stony meteorites. It is shown that within errors of observation the compositions of all samples are alike with the exception that hydrogen is conspicuously deficient in the earth's crust and in meteorites and is probably much more abundant in the chromosphere than in the reversing layer

The eclipse of 1936 was observed throughout Siberia and Japan with much interference from clouds while the 1937 eclipse had clear skies everywhere In 1936, the British expedition in Japan under the direction of Stratton obtained excellent results in spite of many clouds, while in Siberia the Harvard-Massachusetts Institute of Technology expedition under the guidance of Menzel secured carefully standardized and calibrated spectra with large dispersion in the spectral region 3200-10000 angstroms. In Siberia, Williams found 12 new lines in the chromosphere in the infra-red with wavelengths between 9000 and 10049 A He also photographed eight lines of the Paschen series of hydrogen At the 1937 eclipse on Canton Island, Dunham secured spectra of the chromosphere and corona with large dispersion and jumping-film Mitchell obtained spectra with three concave gratings without slit In the infra-red with the Allegheny grating he photographed the strong calcium triplet and also 25 lines of the Paschen series of hydrogen. Also he photographed the strong coronium line at 7892 A, the line discovered in 1925 by Curtis and Burns using the same grating

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[18] *Astrophysical Journal*, 77, 1, 1933

At the 1936 eclipse from spectra taken outside of totality, Royds[19] of the British expedition found that the red shift at the sun's limb is the same in amount inside and outside an eclipse, thus ruling out the possibility that scattering in the earth's atmosphere is the explanation why strong and weak spectral lines show different relativity shifts. In the same expedition, Thackeray[20] finds that the intensities of lines in the Balmer series of hydrogen are in close agreement with the theory of Menzel that the hydrogen lines owe their intensities to some form of excitation in addition to straight electron capture. From the 1937 eclipse Mitchell finds a similar agreement for the intensities of the Paschen series of hydrogen.

Menzel[21] and others at Harvard have published valuable results from the 1932 spectra Information is given about multiplet intensities and density gradients, self-reversal of hydrogen lines and the general theory of curves of growth and self-reversal of emission lines Mitchell has nearly ready for publication a discussion of the October 21, 1930 eclipse which will give a redetermination of heights and the density distribution of gases in the chromosphere. This discussion was aided by a grant from the Penrose Fund.

On account of the great activity in recent years of eclipse observers, particularly the American and British, most of the problems have been cleared up that might be attempted by interested amateurs with moderate equipment. There are many mysteries still connected with the corona, with the chromosphere and with the relativity displacements. For instance, from spectra taken at the 1936 eclipse it was found by Thackeray[20] that the emission lines of neutral metals show an unexplained displacement to the violet relative to limb absorption. The emission lines in the chromosphere, if secured with excellent definition can give valuable information about line profiles which in turn will give further information about the structure of the atom and the mechanism whereby lines in spectra are produced.

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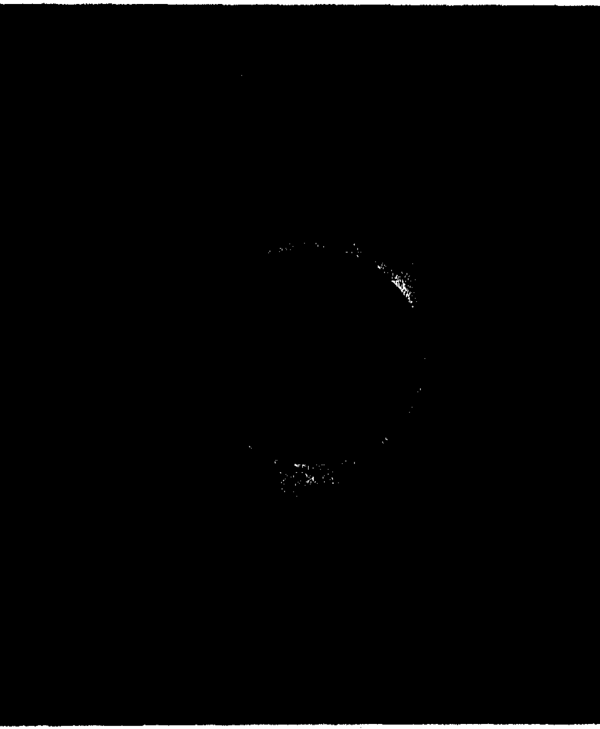
[19] *Monthly Notices*, 97, 692, 1937

[20] Ibid, 672, 1937

[21] Harvard Circ, 410, 1935

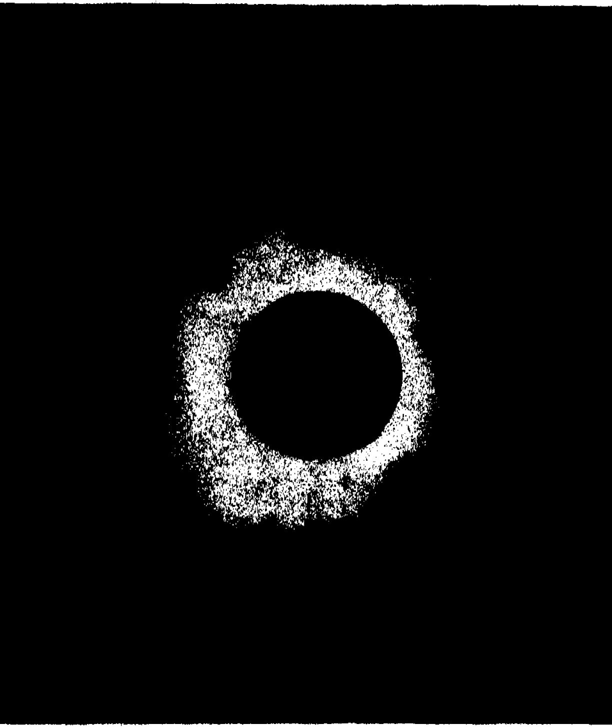
In planning for future eclipses, the British have a great advantage over us in the United States for the reason that our British cousins see each other very frequently at the monthly meetings of the Royal Astronomical Society With us in the United States eclipse expeditions become possible only when some interested person is able to raise the rather large amount of money necessary, while in Great Britain the expeditions are handled more efficiently by the Joint Permanent Eclipse Committee organized under the auspices of the Royal Society and Royal Astronomical Society.

PLATE I



he total solar eclipse of June 8, 1937, made with 10 seconds ex . Irvine C. Gardner of the National Bureau of Standards, a m National Geographic Society–United States Navy Eclipse E o Canton Island in the mid-Pacific. This photograph was take nera designed by Dr. Gardner and built at the National Bur ards. It has a nine-inch astrographic lens composed of four se onents.

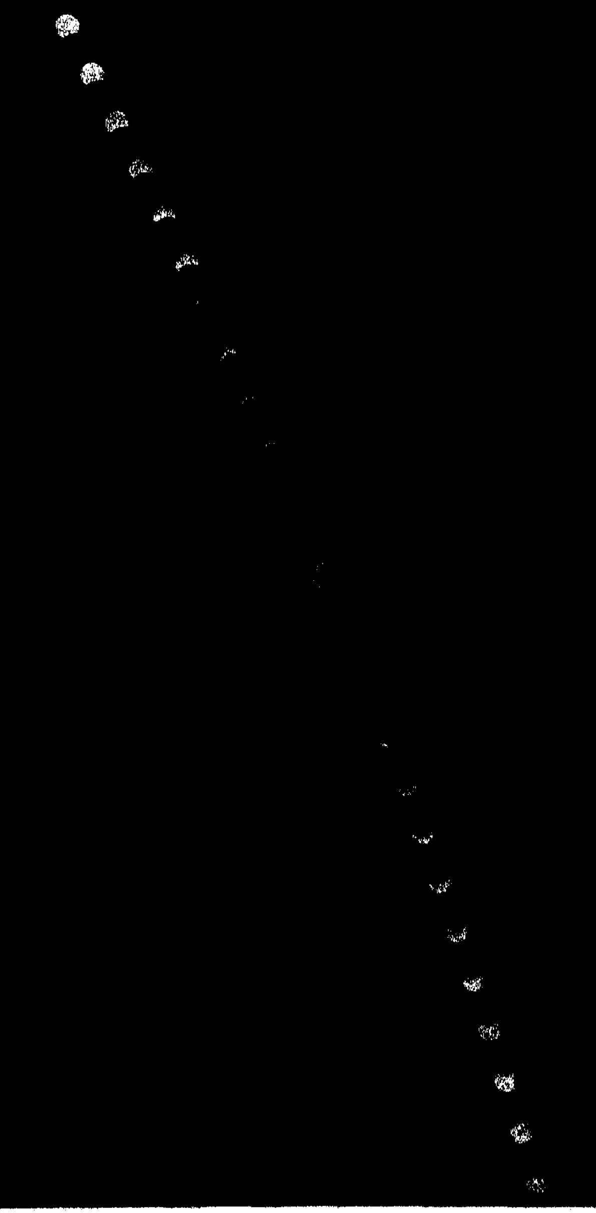
PLATE II



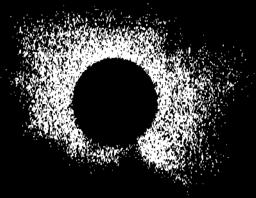
The 1937 Corona

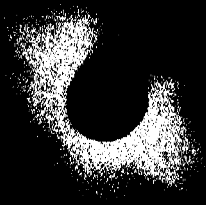
graphed with a camera of six inches aperture and fifteen feet
by *John E. Willis, of the U. S. Naval Observatory*, a member o
nal Geographic Society–United States Navy Expedition. Ti
ure 24 seconds.

The Eclipse Camp on Canton Island



The Progress of the 1937 Eclipse





VITRIFICATION AND CRYSTALLIZATION OF PROTOPHYTA AT LOW TEMPERATURES

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(Communicated by Detlev W. Bronk)

ABSTRACT

I. *Theoretical Considerations*

The conditions which determine whether a homogeneous liquid will solidify into the crystalline or into the vitreous state are discussed and a brief account of the rôle of the speed of crystallization, V, and that of grain formation, N, is given.

These concepts are applied to the causes of the death due to crystallization of non-dehydrated organic cells, and the physical conditions of cooling are developed under which such organisms can be solidified with a minimum of crystallization, assuring to this extent the preservation of their potential life.

II. *Experimental Procedure*

A method of staining cells of certain types (yeasts) which is indicative of their living or dead condition is described. Thus the death rate, δ, for exposure to low temperatures under different conditions, can be determined by direct count.

Different techniques of exposure favoring and preventing crystallization are developed.

III. *Experimental Results*

The rate of cooling of suspensions of living cells in aqueous media was varied from 1 to 10^4 deg sec^{-1} and thus conditions favoring either crystallization or vitrification of the cell plasma were produced. The death rate at an exposure of − 185° C was thus varied from approximately 75 per cent to approximately 3 per cent.

The duration of exposure at this temperature was varied from 5′ to 6000′, no appreciable influence of the time of exposure was found.

The temperature to which the cells were cooled was varied from the boiling point of liquid air (− ° C) to the boiling point of liquid hydrogen (− 252° C) without appreciable influence on the death rate. Indications, however, were found that at − 50° C the duration of exposure affects the death rate.

Repeated exposures of the same cells under conditions not especially favoring vitrification were studied and the integral death rate, δ_n (death rate after *n*th exposure) was investigated with respect to a constancy of the death rate (δ) at each freezing. It appears that the death rate for repeated freezings is not controlled by simple probability relations, but that other effects enter such as weakening of cells by previous exposures and the selection of cold-resistant cells by survival.

I. THEORETICAL CONSIDERATIONS

(a) Crystallization and Vitrification

THE transition from the liquid into the solid state by lowering the temperature of the system can occur in two ways.

In one case the liquid phase changes into the crystalline; the act of crystallization is then characterized by the emission of heat of fusion. Thermodynamically speaking, the crystallization reduces the entropy of the system as well as the heat content $\left(\int_0^T QdT\right)$, the free energy is a minimum (strictly true only for an ideal crystal) and the state is thus the most stable for this particular temperature, and, in general, in the absence of allotropy, the most stable down to the lower end of the temperature scale

Experience has shown, however, that in spite of the high stability of the crystalline state, crystallization does not necessarily take place In other words, the actual occurrence of crystallization depends on a number of statistical conditions which, if not fulfilled in the experiment, prevent the liquid from the attainment of a state of larger stability (higher degree of order) In such cases the system remains a "liquid" for the rest of the temperature scale Needless to say, the word "liquid" refers in this connection to the statistical arrangement of the molecules of the system, in contradistinction to the regularity of the arrangement in a crystal. It does not refer to a number of other physical qualities such as viscosity, etc. In fact, the viscosity soon increases with decreasing temperature to such an extent that the substance is physically solid but not a crystal This state is generally called the glassy or vitreous state * It is physically characterized by a continuous increase of the viscosity as the temperature is

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* The following scheme is rather descriptive of the state of a system, representing all possible combinations

1 Solid	2 Liquid
a Crystal (anisotropic)	*b* Glass (isotropic)

1*a* is a crystalline solid, 2*b* a normal monomolecular liquid, 1*b* a vitreous solid, 2*a* a crystalline liquid (certain organic liquids and probably the second modification of liquid helium) A glass would thus be represented by 1*b* lowered, by a remaining isotropy and by the absence of any discontinuity at the melting temperature, thermodynamically it is characterized by a higher entropy as well as a higher heat content, the latter resulting from the fact that the heat of fusion remains within the system (Fig 1.)

The factors that determine which of the two states will occur when the liquid is brought below its melting temperature are several, and, as they have important bearings on the problem, will be briefly outlined.

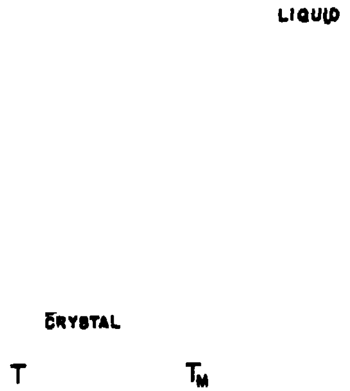
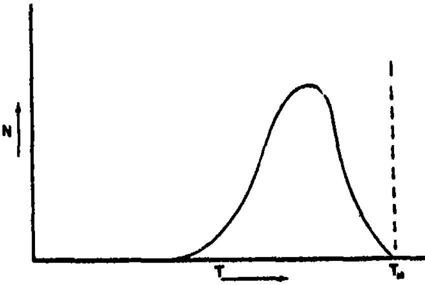


Fig 1 $Q(T)$—Diagram for the liquid, vitreous and crystalline state of a substance in general (T_m = temperature of fusion)

Tammann[1] gave the first systematic description of the tendency of a supercooled liquid to form "grains," *i e.*, nuclear centers of crystallization within itself, and defined the number N of such centers originating at constant temperature per unit time in a unit volume as a characteristic constant for a particular substance. He also showed that N depends upon the temperature in a way as shown qualitatively in Fig 2*a*, at T_m (melting temperature) N is zero, but increases rapidly to a maximum value at a temperature in the vicinity of T_m. It then decreases again and disappears at lower temperatures. The reason for this latter behavior is obviously due to the rapidly decreasing mobility of the molecules at lower temperatures, so that one would expect the decline to be proportional to the increase of the viscosity Aside from this, N depends in the most general way upon the probability of the formation of centers within the system. This probability is obviously controlled by the following factors the number of molecules within the system, the mobility of the molecules within the liquid and the configuration of the crystal lattice characteristic for the particular liquid Qualitatively speaking, it can be said that the smaller the symmetry of the crystal lattice and the farther the molecular configuration of the lattice is removed from that of close packing, the less is the probability of the formation of a nucleus[2] Finally, certain other factors have to be considered, such as molecular association at temperatures slightly above the melting point (H_2O) as well as the presence of surfaces within the liquid such as colloids and suspended particles in general



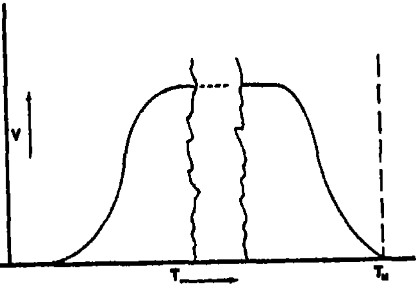


FIG 2a $N(T)$—Diagram representing the variation of the formation of crystallization centers with temperature

FIG 2b $V(T)$—Diagram representing the variation of the linear rate of crystallization with temperature In the omitted temperature interval V remains constant

The second main factor is the linear rate of crystallization V, which characterizes a liquid in a way similar to N and has also a qualitatively similar dependence on the temperature; as shown in Fig. 2b, it rises from zero to $T \leq T_m$, attains a maximum, remains constant for a certain interval and then declines towards zero The causes of this behavior are somewhat analogous to, although more complex than, those for N.

The difference between a substance with a high N and a small V and one with a small N for a large V is that under the same cooling conditions a polycrystalline conglomerate would result in the former, and an oligo- or even single-crystalline habitus in the latter case One can thus predict that liquids with small N and small V should have a tendency to vitrify, provided they are cooled sufficiently *rapidly* to a temperature where N and V are negligible

One result of these considerations is that it should be possible to obtain every substance in either a vitreous or a crystalline state, provided that the proper conditions are maintained during the critical interval of temperature where N and V have large values This postulate, however, has been verified for only a limited number of substances.

(b) *The Rôle of Crystallization in the Cold Death of Cells*

The irreversible changes which organic matter undergoes when exposed to low temperatures are of so involved a nature that even for the limited field of this paper certain general remarks have to be made

From the highly diversified literature on the subject of exposing live matter to temperatures below room temperature[3] it is evident that there exists a form of cold death which may be termed "*constitutional*" (*CD*). It occurs if the organism is kept below its normal temperature longer than its energy supply lasts for counterbalancing the adverse effects of the cold It is obvious that this *CD* can occur at any subnormal temperature before freezing, but the time factor as well as the type of organism will have a large influence upon the effects observed The phenomenon of *CD* is outside the scope of this paper

The other type of destruction of organic matter due to low temperatures is that caused by the crystallization of the cell plasma or liquids surrounding the cell, causing either a rupture of the cell membranes or some form of irreversible disorder within the cell so that after thawing, the cell does not resume its activities characteristic for the live state This phenomenon shall henceforth be called "*physical*" cold death (*PD*) When death occurs below the freezing point this *PD* as the only death cause is apparently restricted to the simplest forms of life, whereas, for higher forms it is often not possible to decide whether *CD* or *PD* caused the destruction The numerous reports and experiments which claim the occurrence of "supercooling" in live matter fall into this realm It has been described by several authors[4] that live cells have the tendency to supercool, that is, that the cell content remains liquid although the temperature stays below zero. If the temperature is reversed *before* crystallization starts, the process proves to be reversible, *i e*, the cell remains alive Very early similar phenomena have been found by Bachmetiew[5] on fairly high forms of organic matter, such as larvae of insects, which proved to be able to supercool over fairly large ranges down to – 15° where crystallization suddenly started, causing the death of the organism The well known freezing curve Fig 3, demonstrates that the irreversibility sets in with the beginning of spontaneous crystallization, indicated by the sudden rise of temperature from the minimum temperature to the freezing point, due to the display of the heat of crystalliza-

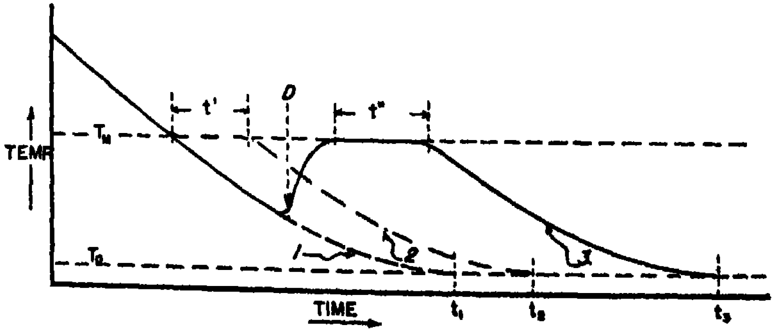


Fig 3 Temperature-time function for (1) continuously cooling substance, (2) substance crystallizing at T_m, remaining at T_m for the time t', (3) substance super-cooling down to *D* Due to the emission of the heat of crystallization *T* rises to T_m for the time t'' Type (3) is characteristic for organic substance Death sets in at *D*

tion. As soon as the organism is made to display this heat, death occurs. There seems to be no doubt that this death is *PD*, although it is not easily decided whether the tendencies towards supercooling characteristic for live organisms are of a constitutional or a physical nature.

It is, however, definitely proven that there are numerous species of organisms to which the *CD* does not apply, as shown by the experiments on thoroughly dehydrated protozoan [6] and even metazoan [7] forms which withstood, without particular precautions, temperatures down to the boiling point of He (4 2° K.). In these cases the *PD* was avoided by complete dehydration so that no substance for crystallization was present Experiments of this type are of course restricted to seeds, spores and infusoria, and it is also obvious that neither the time of exposure nor the temperature has any influence.

The question arising from these known phenomena is· is it possible to expose *non-dehydrated* organisms to low temperatures without destroying their potential life? It is known for a number of bacteria, moulds and fungi which contain only very small quantities of liquids, that they survive very low temperatures without dehydration, whereas, it is also known that the majority of protozoa and plants cannot be cooled without the destruction of life

(c) *Conditions of Vitrification*

It has been stated above that the *PD* consists in the crystallization of the cell plasma This leads to the assumption that if conditions under which the organism is cooled can be so arranged that vitrification is more probable than crystallization, the *PD* should be avoided. In contradistinction to crystallization, vitrification would not disturb the molecular arrangement of the cell contents, and also, the more macroscopic effect of crystallization, the lesion of the cell membrane, is impossible.

The greatest handicap in experiments connected with the vitrification of water and diluted aqueous solutions is the unusually high value of N and V (see I, *a*) which render any attempts at the vitrification of organisms very difficult.

The fundamental conditions to be fulfilled for obtaining the vitreous state are the following ones

1 Since for a given value of N the probability for the formation of a nucleus in a given system depends upon the *number of molecules available*, the system should be chosen as *small* as possible, *i e*, to contain a minimum of molecules The minimum size of a system for organic matter is a single cell, among different cells the smallest should have the largest probability of vitrification

2 For a given N and a given number of molecules, the probability of the occurrence of a nucleus depends upon the temperature (in the way shown in Fig 2*a*) and the time during which the system is at a certain temperature As N decreases exponentially towards low temperatures after the maximum, it is very important to *cool* the system *as quickly as possible* over the temperature interval in which N has large values Below this "critical" temperature interval, the cooling rate is of no importance as far as N is concerned From this it is obvious that the ultimate temperature to which the system is cooled is irrelevant as long as it lies below the "critical" temperature range.

3. It has been stated above that N depends upon the complexity of the molecular configuration in the crystal. As it is not possible to change the chemical constitution of the aqueous solution within and around the organism without damage to the latter, the only way consists in increasing the surface exposed to the liquid, this can be accomplished by the addition of complex colloidal matter causing, due to the increase of molecular complexity, a decrease of N Such substances (hydrosoles of organic substances) are gelatine, agars, glues, the addition of which does not affect the organism.

4. The spontaneous rate of crystallization depends upon almost the same physical factors as N, accordingly, the conditions for vitrification with respect to N hold also for V, with

the possible exception of 3, in which latter case the addition of colloidal matter reduces V in certain cases

It is generally to be assumed that V is a much more critical factor than N for the avoidance of PD * In order to control V, it is necessary to consider the critical temperature interval for V just as accurately as for N Another point to be considered with respect to V is the *time of exposure* to low temperatures. As V, for thermodynamic reasons, will become zero only at zero temperature, it is to be expected that a gradual, though slow, crystallization out of the statistical arrangement of the glass will go on with time One should therefore expect that the time of exposure will have an effect upon the probability of the survival of the organism unless the temperature is chosen so low that the value of V is sufficiently small to be negligible for time intervals on a terrestial scale.

5 If it is desired to warm the vitrified substance while preserving the capacity for life, condition 2 has to be fulfilled in *warming as well as in cooling* in order to avoid crystallization when the substance passes the critical temperature interval in the direction towards room temperature If the final temperature be chosen sufficiently low (that of liquid air) the warming process is not as critical as the cooling process in this particular regard, because the critical temperature interval for aqueous solutions ends at approximately − 110° C.[8] so that an interval of 70° is available for the time of transfer from one bath to the other, where the warming rate cannot be forced

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* It can be taken as a generally accepted fact that a perfect crystal is just as well an ideal abstraction as a perfect glass The X-ray spectroscopic evidence has not yet proved the existence of either of the ideal states In the case of the vitreous substances, even fused quartz has been proven to contain small realms of crystalline molecular array, the dimensions of which are far below the limit of optical detectability To speak of the vitreous state of a cell is thus an inaccuracy and means that a cell is "vitrified" if the size of the crystalline realms are smaller than dimensions fatal for the particular cell This relation may serve to explain that organisms of different types but of approximately the same dimensions and structure cooled under identical conditions do not survive with the same probability The size of the realms is determined by V, whereas N determines their concentration

II. EXPERIMENTAL PROCEDURE

(a) *Determination of the Death Rate δ*

A quantitative experimental study of the *PD* or organic matter requires, besides an adequate experimental technique for the production of the conditions of vitrification, the establishment of a definite criterion of the live or dead state of the cell The most obvious way is the growth of cultures of cells treated, if the organisms represent bacteria, fungi or protozoa easily cultivated This technique has been used generally in the work quoted,[6] also in the first experiments of the authors It is, however, not indicative of the actual death rate because of the purely qualitative indication of the existence of some or even *one* surviving cell Furthermore, such experiments which require absolute sterility in order to obtain positive results, seem offhand undesirable and to be chosen only if no other method is possible

Another way, which has the advantage of measuring directly the death rate δ, that is, the ratio of dead cells to the total number of cells present, is the use of motile protozoa where the sample can be counted before and after exposure, δ is then established by the count of the still and the moving organisms This method also was tried extensively It turned out, however, that it is often very difficult to distinguish between a dead organism and one in a state of rest, which state most motile forms can enter

It was therefore considered most fortunate that a method of differential staining was found applicable which permits visual distinction between dead and live cells. Experiments of the authors on a large variety of organisms showed that the use of colloidal stains is not necessarily indicative for *PD*, but that stains of the type of methylene blue, which are not in general considered colloidal,* can serve as very reliable indicators if a number of precautions are taken Such dyes have lethal effects if too concentrated and it is necessary to find for each type of organism the proper concentration, which latter obviously consists in a compromise between a concentration high enough to give a well stained effect upon the dead cell, though at the same time small enough not to have lethal effects within the time of observation

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* It is known that a number of stains, most of them, however, of a colloidal character, such as congo red and trypan blue, do not affect certain organisms while they are alive, and that the dye can stay in contact with the cells for a considerable length of time if not too concentrated Seyderhelm and collaborators,[9] used a mixture of congo red and trypan blue known as "Seyderhelm stain" It was applied first to leucocytes as a differential stain and also to protozoa.[10]

This being once accomplished, the technique becomes very simple and seemingly more reliable than any other method if a number of technical precautions are observed The death rate δ is determined simply by placing a drop of the treated culture containing the dye on a slide under the microscope and taking one or several photographs of it An enlargement of the photograph is made and the number of stained and unstained cells counted

Two conditions have to be fulfilled here It is important to filter the illuminating light in order to produce a maximum contrast between the stained and unstained cells, *i.e* , the light should contain chiefly the colors complementary to those of the dye used. This condition being very important, it renders it necessary to find, either by trial and error, or by spectroscopic methods, the proper filter combination for each dye Furthermore, the sensitivity of the photographic emulsion has to be chosen properly The photomicrographs show thus white and black cells which can easily be counted

Secondly, it is important to choose the magnification and the concentration of the preparation in such a manner that a large number of cells (several hundred to several thousand) are on one photograph, in order to obtain fair statistical percentages The errors connected with this method are small and can occur only if more than one layer of cells is in the preparation, as if several cells lie on top of each other, the effect of a dark cell may be created. This can be avoided by applying the following technique the carefully cleaned slide is slightly heated and then covered with a thin layer of cleared gelatine solution The slide is then allowed to cool and dry until the gelatine is almost completely hardened. A concentrated drop of the culture containing the stain is then put upon the gelatine coat and distributed over the latter by rubbing under very gentle pressure with a fingertip until all of the gelatine is equally wetted. A wetted cover-glass is then slipped over the slide and the surplus liquid soaked up with filter paper Investigation has shown that δ is not increased by this manipulation Under low magnification one finds large regions on the preparation consisting of 10^3 to 10^4 individuals in monocellular arrangement. Counts within these realms prove to be very reliable

Another precaution has to be taken if the organisms are sensitive to blue light or to heat In this case they are destroyed during the time of observation by the illuminating light source In such cases it is possible to observe a rapid increase of stained cells within a short time during observation of the slide. This renders it necessary to use effective heat filters and also to shorten as much as possible the time of exposure to the light

(b) *Techniques of Vitrification*

In the following, a number of different techniques will be briefly described which have been employed by the authors in order to realize experimentally the conditions of vitrification discussed in (I*c*).

Condition 1 calls for small systems of molecules, which means either the isolation of the single cell as the minimum size of a system or, where the cells are small enough, the use of small droplets or thin layers (membranes). This has been done in cases where bacteria were used by spraying liquid cultures through nozzles similar to atomizers. This method is applicable only where the organism is small and has sufficient mechanical resistance to stand the shear to which it is subjected when passing the nozzle at the speeds necessary to atomize the more or less viscous liquid.

If the cells are too delicate, it is possible to resort to a technique which produces a thin membrane of the cell-containing culture medium in a large platinum loop. In this case the largest surface possible for a given volume can be created in a relatively simple manner

Condition 2 requires a high rate of cooling over the critical temperature interval, which is not as easily realized. It is obvious that the culture medium should be brought in contact with the low temperature bath as quickly as possible, and also that this bath should have a temperature as low as conveniently possible, *e g*, that of liquid air (90° K). This can be done by shooting the spray under pressure into the cooling bath, or by dropping the membrane with its holder as quickly as possible into it Experiments prove, however, that all such efforts to overcome *V* with the cooling rate are rendered futile by the "Leidenfrost phenomenon" which consists of the formation of an insulating gas layer around the warm object, rendering a quick temperature exchange impossible It is obvious that this phenomenon will always occur when the *boiling point of the cooling medium lies below room temperature*, *i e*, the temperature of the medium at its introduction As the cooling bath has to have a very low temperature, only very few substances for such cooling purposes are available (as they must also be liquid at low temperature)

Another condition has to be imposed upon this substance which is also imperative—it must be insoluble in water The only substance which was found to fulfill these conditions is iso-pentane (C_5H_{12}) with a boiling point at 28° C and a melting point at − 159 6° C [11] * As iso-pentane has, like most other substances of very low crystallization temperatures, small values for *N* and *V*, it can be undercooled to the boiling point of N_2, where it remains a clear liquid of syrupy consistency. Fig 4 shows the arrangement where a container with iso-pentane is submerged into a Dewar vessel containing liquid air The temperature of the pentane is easily measured with a thermo-couple or pentane thermometer.

The realization of condition 5 is also easily obtained with the use of volatile hydrocarbons; the substance is transferred as rapidly as possible from the pentane bath into a bath of petrol-ether at room temperature and is moved vigorously in the latter, in order to further a rapid temperature exchange.

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* The use of isopentane for such experiments is only possible since it does not affect the cells as a solvent nor by any observable chemical reaction

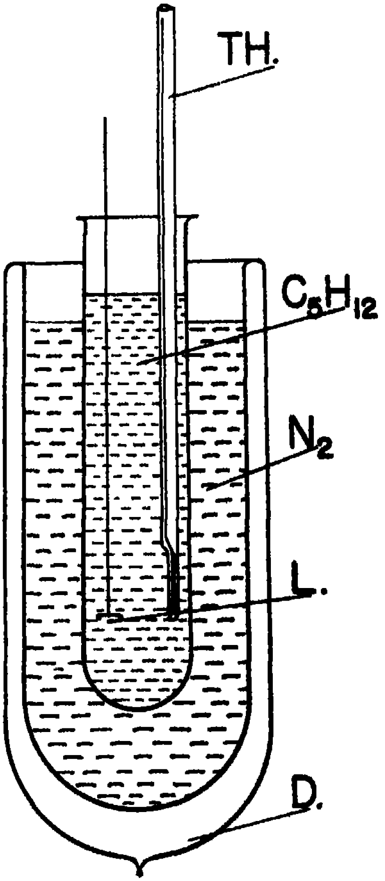
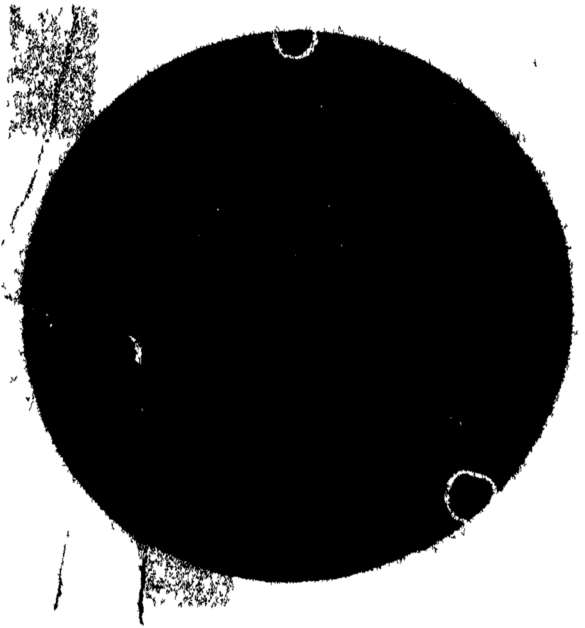


FIG 4 Scheme of cooling apparatus *D*, Dewar-vessel containing liquid nitrogen (N_2), suspended in it a container with iso-pentane (C_5H_{12}); *Th*, pentane thermometer, *L*, submerged platinum loop holding culture membrane

Condition 3 may find its fulfillment in a number of ways. The introduction of gelatine has been used fairly early in the work, and observations similar to those of Luyet [12] have been made

The process of vitrifying thus goes on as follows
id culture medium (cf. below) is introduced in
aying mechanism and sprayed into the pentane bath
h liquid air; or the culture medium is brought into th
drop being thinned to the point where the membra
nes almost unstable. Then the membrane is dip
idly as possible into the pentane bath. For warmi



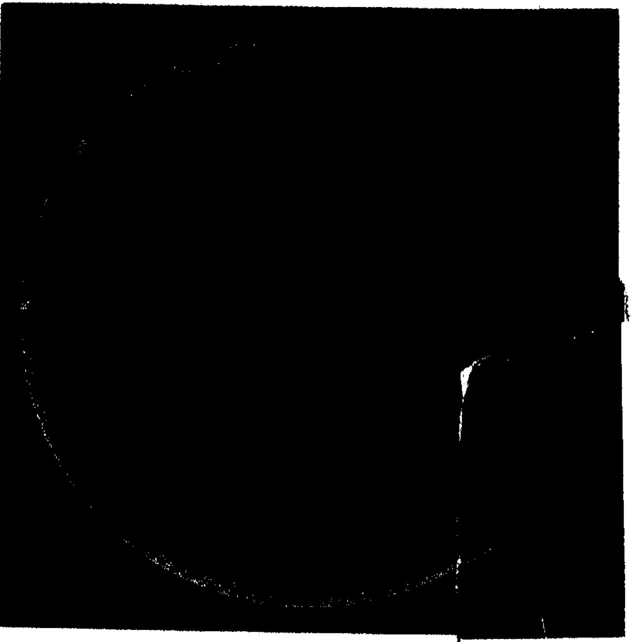
IG 5 Ultramicroscopic photograph of monocellular layer of
cerevisiae (cardioid condenser, obj apochr. 20 ×, magn. 250
hrome).

contents of the pentane bath are transferred as r
ssible into the ether bath at room temperature.
nen placed upon a microscopic slide, the indicato
ded in the proper concentration (cf. II*a*) and after

numbers δ is determined.

(c) *The Use of Yeast* (Saccharomyces Cerevisiae)

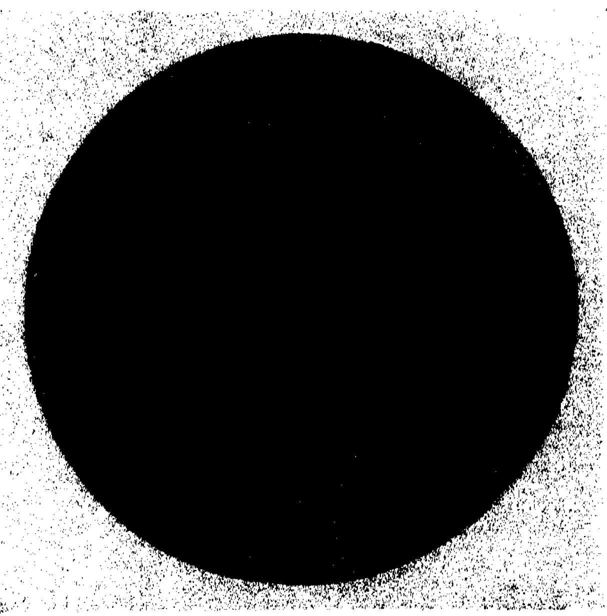
ith regard to the considerations of II*a*, it seemed a
o choose organisms for the low temperature experim



6. Microphotograph of unexposed *Saccharomyces cerevisiae* (apl
apochr. 20 ×, magn. 250, orange + green filter, Agfa Superpan, tu

are easily obtainable in pure culture, and wher
dual cells are large enough not to necessitate the
scopic objectives of extremely short focal length, ca
racies in the counts. The chief condition for e
of surveying character

the time of the experiment.
e yeast was obtained as commercial bread yea
ded in Ringer's solution, where it remains stabl
r of hours. For each set of experiments new yea
his procedure was chosen as it proved to give mo
esults than those obtained with the same yeast

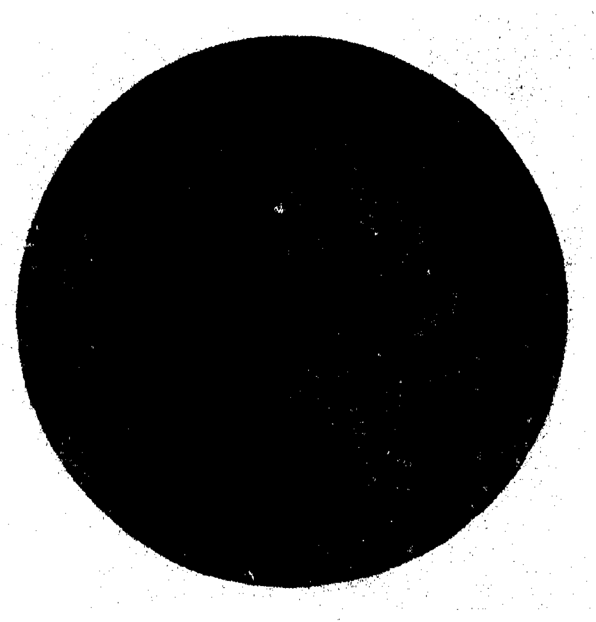


7. Microphotograph of *Saccharomyces cerevisiae* once exp
C. under vitrifying conditions (apl. cond. 1.4, obj. apochr. 20 ×
ellow filter, Agfa Superpan, tungsten arc).

quid nutrient media. Another advantage is th
or staining method showed an equal resistance
lls to the stain, whereas cells taken from a nu
show a varying percentage of individuals suscept
in.

d in the ultra-microscope, where the superposi
lls can be seen if present. Fig. 5 presents an
opic view of such a monocellular layer of Sac
cerevisiae.

counting purposes, however, direct illumination
d since the ultra-microscope does not permit
tion between stained and unstained yeast cells.



8. Microphotograph of *Saccharomyces cerevisiae* once exp
. (apl. cond. 1.4, obj. apochr. 20 ×, magn. 250 ×, orange filt
, tungsten arc).

III. Experimental Results

) *Death Rate under Conditions Especially Favorab to Crystallization*

e yeast was suspended in Ringer's solution in cond

The preparation was left at this temperature for a few minutes and then warmed to room temperature. The death rates thus obtained varied considerably for different experiments, as the method used did not permit of the exact reproduction of the cooling rates. The average values obtained are given in Table 1.

TABLE 1

Approx. cooling rate (deg sec^{-1})	20	6	3	1
Approx. death rate (δ)	0.29	0.49	0.70	0.75

There are indications that with further decrease of the cooling rate a death rate of 100 per cent ($\delta = 1$) can be reached.

(b) *Death Rate under Conditions Especially Favorable to Vitrification*

The next step consisted in reversing the physical conditions of cooling by applying the principles set forth in Chap. IIc.

The quantitative results presented in Table 2 are obtained with the loop-method (Chap. IIb) for T_0 between $-150°$ C and $-185°$ C on yeast suspensions identical in nature, age, etc., with the suspensions used previously.

TABLE 2

($v \sim 10^3$ to 10^4 deg sec^{-1})

t	N	D	δ	δ'
0	639	7	$0.011 = \delta_0$	
Circ. 2′	2232	194	0.087	0.076
Circ. 2′	1071	141	0.131	0.120
Total	*3303*		Average	0.098

As the submersion was done by hand the rate of cooling ($v = dt/dt$) is not expected to be the same in different experiments, for large values of v are required in view of the magnitude of V for aqueous solutions. In the subsequent tables the following symbols are used

t = Time of exposure,
N = Total number of cells present in the photograph,
D = Number of stained cells,
$\delta = \frac{D}{N}$ = Apparent death rate,
δ_0 = Death rate already existing in the preparation before exposure to low temperature,
$\delta' = \delta - \delta_0$ = Actual death rate by exposure,
v = Rate of cooling.

Figs 6 and 7 represent photomicrographs of preparations before and after exposure under these conditions.

In accordance with condition 3 (Chap I*c*) the effect of colloidal admixtures upon δ was tested with the following results (C_g gelatine concentration)

TABLE 3

($v \sim 10^3$ to 10^4 deg sec^{-1})

C_g	t	N	D	δ	δ'
0	0	822	57	0 069 = δ_0	—
1/2500	2′	501	74	0 147	0 078
1/250	2′	447	67	0 149	0 080
1/50	2′	390	50	0 128	0 059

Although the material so far collected is not sufficient in volume for a final quantitative statement it is evident that

1. exposure to low temperatures under vitrifying conditions increases the percentage of surviving cells from 25 per cent to 90 per cent.
2. addition of gelatine decreases δ still further *

This appears to prove the previous postulate that *PD and crystallization of the cell are defined functions of each other, and*

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* The results in table 2 are unfavorable to δ because of the high value of δ_0 which indicates a low vitality of the particular preparation used

that by supressing the crystallization the death rate can be controlled

The definite proof depends upon a quantitative determination of $\delta = f(v)_T$, for which the primitive methods employed so far are insufficient. Results with improved apparatus will be published soon.

(·) *Death Rate under Conditions Favoring the Coexistence of the Vitreous and the Crystalline State*

In order to determine the influence of the temperature, duration of exposure etc , the cooling conditions for the following experiments were chosen so that δ ranged reproducibly between 0.25 and 0.50 in order to dispense with the necessity of counting very large numbers of cells for obtaining sufficient accuracy.

1. Death rate as function of duration of exposure to low temperatures ($\delta = f(t)_T$)

The procedure of cooling chosen to meet the above condition for the study of the variation of δ with t, was as follows

A given quantity (5 c c) of a standard suspension of yeast in Ringer's Solution was put into a test tube and submerged in liquid air, in order that a relatively slow cooling rate might obtain A number of tubes were prepared in this manner and exposed for different lengths of time to − 185° C., the shortest time being 5′ (the minimum time for the complete cooling and thawing process) the longest 6000′ Precautions were taken that the warming speed be the same for all samples The slides were then prepared according to the above method and the results, condensed in Table 4, were obtained

In Fig 9 the results are plotted vs the logarithm of the time of exposure, where the diameters of the circles (●) represent the estimated accuracy of the counts

The results obtained show a good consistency of the values and indicate that, in agreement with postulate of condition 4 in Ic *the duration of exposure does not affect* δ, even if T is

TABLE 4

t	lgt	N	D	δ	
0		1312	16	0.012 = δ_0	
5′	0.70	1309	405	0.309	0.318
5′	"	1017	334	0.328	
17′	1.23	1252	391	0.312	0.324
17′	"	1191	402	0.337	
60′	1.78	2145	655	0.305	
120′	2.08	1489	431	0.289	
210′	2.32	1216	348	0.285	
1080′	3.03	858	291	0.339	
600′0	3.78	1976	641	0.324	
Total		*12453*	Average	0.312	

varied by a factor > 1000, *if the temperature is far below the critical temperature interval.*

The reaction of an older yeast suspension (48 h) to − 185° C. under the same conditions shows a higher δ (0.48), indicated in Fig. 9 as ●

2. Death rate as function of temperature ($\delta = f(T)_t$).

In order to test the conclusion made previously that below the "critical" temperature range the temperature should not have any influence upon the death rate, a preparation identical with those described in (III.*c*.1) was exposed to the boiling temperature of hydrogen (− 252° C.). The experiment was performed as follows. 1 c.c of the suspension was sealed in a glass tube and submerged first in liquid air for the purpose of precooling. It was then transferred quickly into a container of liquid hydrogen and left there for approximately four hours. It was then transferred again into a liquid air bath, where it remained 24 hours. Then it was warmed to room temperature

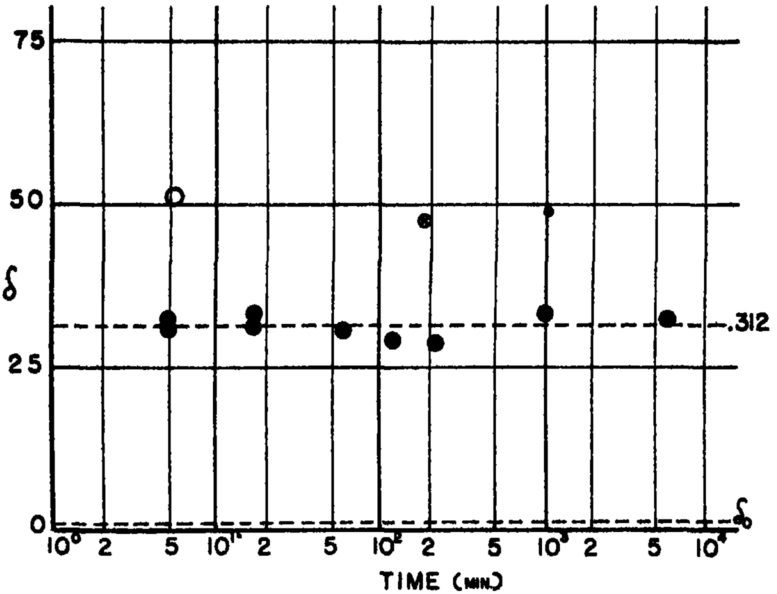

FIG 9 $\delta(t)$—Diagram representing the invariance of the death rate with time of exposure, the latter being represented on a logarithmic scale δ_0 = death rate for the unexposed suspension, ● for fresh suspension at − 185° C, • old suspension at − 185° C, ○ for fresh suspension exposed to − 50° C ⊕ old susp at − 252° C

at the normal rate, after which δ was measured in the usual manner

The suspension was of 48-hour age, characterized at liquid air temperature by $\delta = 0.48$ (see III.*c* 1). The value obtained in the liquid air—hydrogen exposure (⊕) proved to be $\delta = 0.46$, which is, within the experimental error, identical with the liquid air value This indicates *the invariance of δ with T below the critical temperature range*

Although sufficient data are not yet available for a reliable indication, it may be mentioned that similar experiments have been performed at − 50° C, that is, within the critical temperature range (marked by ○ in Fig. 9) by means of pentane cooled in a solution of CO_2 in acetone. The value of δ, under otherwise similar conditions, proves to be about 0.5 for an exposure of several minutes for a freshly made suspension, *i.e.*, 18 per cent higher than the average $\delta = 0\ 31$ for a fresh suspension at − 185° C

c Death rate as function of the number of repeated exposures to low temperature $(\delta_n = f(n)_{t,\ T_0}$

A different type of experiment can be devised in order to gain insight regarding the nature of *PD* in organic matter from another angle.

If the same sample is *repeatedly exposed* to low temperatures under identical cooling and warming conditions (v, T_0), the following simple mathematical consideration should be applicable If N is the total number of cells, D_n the number stained (dead), L_n the number unstained (alive), both after n the nth exposure, then $\delta = D_1/N$, $\lambda = L_1/N$, $\delta = (1 - \lambda)$ after the first exposure The total death rate (determined by count) after the nth exposure is therefore:

$$\delta_n = f(n)_{v,\ T_0} = \sum_1^n \delta\ \lambda^{n-1} = \frac{\delta(\lambda^n - 1)}{\lambda - 1} = 1 - \lambda^n$$

The experiments were conducted under similar conditions to those described in III.*c*.1, *i e*, for medium values of $\delta(= \delta_1)$ Table 5 represents the results together with calculated values of δ_n for comparison

TABLE 5

n	N	D_n	δ_n	$\delta_n = (1 - \lambda^n)\delta_1$	$\delta_n = (1 - \lambda^n)\delta_2$
0	1312	16	0 012	—	—
1	1200	401	0 333	0 333	0 423
2	1359	902	0 667	0 552	0 667
3	1370	1070	0 781	0 700	0 808
4	840	669	0 796	0 799	0 889
5	—	—	—	0 865	0 936
Total	6081				

Figure 10 illustrates the difference between the experimental and the theoretical function, which later has been calculated up to $n = 5$ for $\delta = \delta_{1\ \mathrm{exp}}$ and for

$$\delta = 1 - (1 - \delta_2)^{1/2}.$$

The observations show a systematic deviation from the theoretical functions beyond the experimental error, as $\delta_{n\ \mathrm{exp}}$ (n) increases faster for $n = 2, 3$ and again reaches numerical equality for $n = 4$ with the expectation of decreasing below

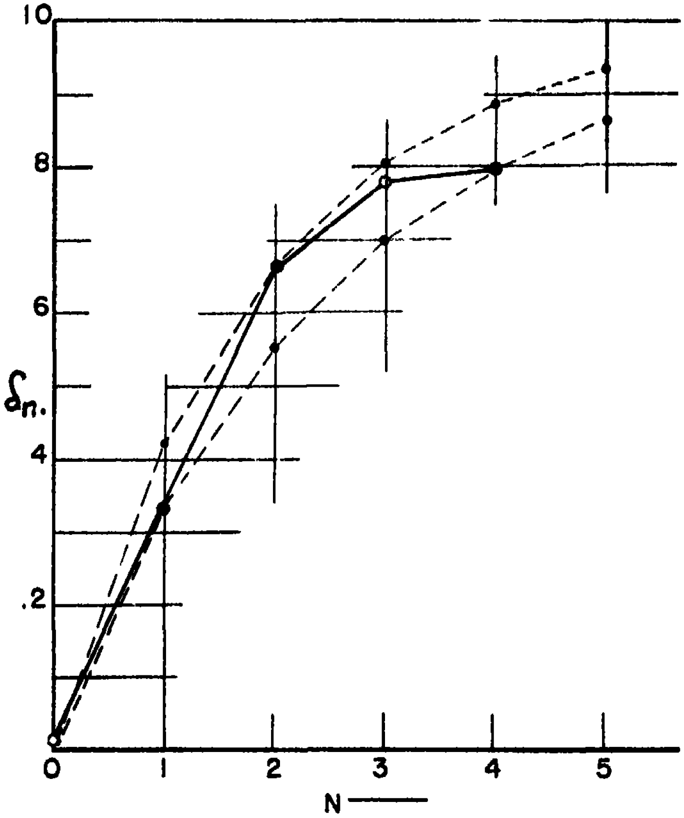

FIG 10 $\delta_n(n)$—Diagram representing the integral death rate after repeated exposure to − 185° C under normal cooling conditions The full drawn lines represent the observations, the dashed lines the prediction for δ = const, the lower for $\delta = \delta_1$, the upper for $\delta = 1 - (1 - \delta_2)^{1/n}$

the theoretical values for $n = 5$ In other words, the behaviour of the function indicates that δ *does not stay constant with repeated exposures*, for δ_2 and δ_3 are larger than δ_1 and δ_4 Although the number of counts and experiments are, up to now, not sufficient for a definite statement, the possible causes for this type of deviation will be briefly discussed.

1. The first exposure weakens a certain fraction of the cells against *PD* but they are not destroyed. These cells cannot resist a second or third exposure and thus contribute largely to δ_2 and δ_3. After all such cells have been destroyed, δ_4 is again normal (the close numerical coincidence for δ_4 in Table 5, is of course to be considered accidental). It is also to be expected that for δ_5 the values would be even smaller than predicted because the remaining cells represent a selection of those with the most resistant qualities.

With this assumption it appears nevertheless surprising that the first exposure does not show the largest death rate

2 A large fraction of cells killed in previous freezings is physically annihilated by crystallization (bursting the cell membrane) during later exposures to alternatingly low and high temperatures Thus with each new freezing, the number of cells killed during previous exposures is gradually decreased, as these burst cells become invisible and drop out of the count

In order to make certain, it is necessary to modify the present method of counting to include a measurement of the concentration of the suspension. Experiments of this type have been performed with the use of a hemacytometer modified for this purpose. The results so far obtained indicate qualitatively that such a phenomenon actually takes place.* Further results along this line will be published soon.

This effect, however, cannot explain the increase of $\delta_{2,3}$ over δ_1, for which only the physiological cause previously discussed appears to account

The possibility of "weakening" cells by exposure gains probability in view of the fact that in these last experiments small cooling velocities were used, possibly allowing time for destruction by *CD*. It is to be expected that the $\delta_n(n)$ function will change considerably for forced cooling conditions. Work in this direction is continued.

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* Recent experiments in which the total population was determined with the counting chamber after each consecutive *n* seem to indicate that the number of cells stays more or less constant and that, in any case, the decrease measured cannot be made to account for this effect

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NEUTRAL PARTICLES IN PHYSICS

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(*Read April 21, 1938*)

ABSTRACT

During the early days of science, the elementary particles which scientists and philosophers alike saw fit to postulate were always imagined as chargeless With the remarkable growth of the understanding of electricity during the nineteenth century, and with the invention of instruments for detecting small charged particles during the twentieth, it became the custom to suppose that the fundamental particles of matter all bear charges and that the forces exhibited in Nature are all electrical (exception being made for gravitation) A noted and serious objection to this view was temporarily met by the adoption of quantum mechanics Since 1930 a reversal of trend has set in, heralded by the discovery of the neutron as a subatomic chargeless particle capable of independent existence, and at present there is a strong tendency to develop the view that neutral as well as charged particles of subatomic size, and non-electrical as well as electrical forces, exist together in Nature

I HOPE that it may entertain you to hear some general remarks on the status of fundamental neutral particles in our present idea of the world Right at the outset I flounder into difficulties with my phrasing, for there is a certain amount of presumption and risk in referring to any known particle by the word "fundamental" Of course there is no objection to applying that word to, let me say, the atoms of Lucretius Lucretius never pretended to have observed the atoms which he talked about, he merely imagined them, and so he could define them in such a way that they couldn't help being fundamental by definition But when a physicist refers to a so-called fundamental particle, he is referring to something which can be and has been observed Therefore he is always exposing himself to the risk that somebody else, or possibly he himself, may some day break it up. It is entirely unsafe to affirm that any of our particles is really ultimate I think that the best way to avoid this linguistic hazard is, to share out the term "fundamental" among several kinds of particles, of which we already know that some are composite and are willing to concede that all the rest may be. Here is my list of today, with symbols at the right to indicate the charges.

1	Atom	0
2	Negative electron	−
3	Nucleus	+
4	Proton	+
5	Neutron	0
6	Positive electron	+
7	Photon (corpuscle of light)	0

The atom which heads the list is not, of course, the imaginary ultimate particle of Lucretius. It is, or rather they are, the chemical atoms—the atoms of the chemical elements Of these we all know that they are composite An atom is in fact regarded as a sort of miniature solar system in which a nucleus plays the role of the sun and a host of negative electrons play the roles of the planets, only, the forces which hold the system together are electrical and not gravitational This is the first of the points—not new points, of course, but very well-known ones—which I want to stress. Our atom-model is electrical entirely, it has none but electrical forces inside it, it is a product and an epitome of the electrical theory of matter. For the best part of forty years, physicists have been systematically denying the right of any but the electrical forces to operate in the heart of matter. Possibly that sounds like an over-statement, in view of the fact that after all no physicist has yet denied gravitation, and the further fact that all our literature is full of allusions to chemical affinities, chemical forces, valence forces, capillarity forces, and I don't know what else. However my statement cannot be attacked on these grounds, for as to gravitation, it has always been considered *sui generis* and recognized as being far too weak to play a great role in the interior of the atom, and as to chemical affinity and capillarity and all the rest, we have long been taking it for granted that all of these forces must be electrical. Indeed I am afraid that physicists have rather got into the habit of regarding as a crank anybody who believes in any forces not electrical! So great has been the prestige of the electrical theory of Nature

An odd thing is, that the electrical theory of matter got itself established with this great prestige despite the broadly-known fact that it is demonstrably impossible. There is a classical theorem to the effect that a system of electrical charges cannot be in stable equilibrium if the charges are at rest, and cannot be in any sort of a durable state at all if the charges are in motion This apparently defeats at the outset the ambition of constructing a thoroughly electrical world Now I am not going to retell you the many-more-than-thricetold story of how Bohr met this difficulty Bohr snatched victory from defeat by deliberately ignoring that theorem You recall how Polonius, after listening to Hamlet for a while, decided that there was method in his madness Well, Bohr's idea *was* a crazy one, as plenty of people in the early days did not hesitate to say, but there proved to be so much method in that madness, that eventually the method came to be worked up into a whole new system of mechanics and the madness ceased to be regarded as madness Now I can amend my statement of a minute ago about the electrical theory of matter. It is the theory that all neutral bodies are aggregates of charged particles and that all the forces in Nature are demonstrations of the electrical forces between these particles, operating according to the new or quantum system of mechanics This is the theory that attained such prestige that it drove the very idea of neutral elementary particles completely out of mind. How completely, I will now illustrate to you

We turn from the atom to the nucleus thereof Looking over any tabulation of the several hundred types of atom-nucleus with which chemists and physicists are already acquainted, we see many places in which two of the types are identical with each other in respect to charge (they are said to be different isotopes of one and the same element) but differ from each other by about one unit of mass. "One unit of mass" signifies a mass about equal to one-sixteenth of the mass of the oxygen atom (It would be necessary to refine these statements with considerable care if in this paper I were concerned with precise mass-values, but for my present purposes these phrasings are not too rough.) Instances of this kind are furnished by Li^6 and Li^7, Li being the symbol of a chemical element, while the superscripts 6 and 7 stand for the masses of two of the nucleus-types belonging to this element, by He^3 and He^4, the two known isotopes of helium, by H^1 and H^2, the famous "ordinary hydrogen" and "heavy hydrogen," of which the nuclei are known by the names of "proton" and "deuteron" respectively It is evident that the simplest way to visualize the Li^7 nucleus is, as a Li^6 nucleus with one extra neutral particle of mass one, that the simplest way to visualize the He^4 nucleus is, as a He^3 nucleus with one extra neutral particle of mass one, that the simplest way to visualize the H^2 nucleus is, as a proton with an extra neutral particle of mass one Yet nearly everyone preferred, until six years ago, to visualize the Li^7 nucleus as a Li^6 nucleus with *two* extra charged particles (proton and negative electron) having equal and opposite charges and a total mass amounting to one mass-unit, and had the heavy isotope of hydrogen been discovered earlier than it was, there would undoubtedly have been a period of visualizing it as consisting of three particles all of them charged and two of them compensating one another's charges (two protons and one negative electron) rather than as consisting of two particles one of them charged and the other not. The simpler model was deliberately rejected in favor of the more complex. This state of mind continued until at last the experts in the art of transmutation managed to operate on the nuclei in such a way as to detach these neutral particles and set them free to wander forth into space and prove their existence in independence.

There are now upwards of a hundred known ways of detaching this hypothetical particle, which on being set free ceases to be hypothetical. Shakespeare said that the poet's pen could give a local habitation and a name to the forms of things unknown, but here the unknown corpuscle acquired a name only on being thrown out of its local habitation The name, of course, is "neutron" The simplest and one of the handiest ways of releasing a neutron consists in projecting one deuteron violently against another, with the aid of a high-voltage machine it then happens—not always, but sometimes—that one of the deuterons takes the proton away from the other, leaving the neutron to go free There are scores of other ways, some of which were sooner discovered When the release of the neutron was definitely confirmed, the world of physics relinquished the nucleus-models till then accepted, and began to imagine the atom-nuclei as systems of protons and neutrons only

But how is the neutron observed when it has been freed? Here comes another important point Since 1932 our minds are no longer constrained to conceive electrical particles only, but our apparatus is still traditionalist The fundamental particles can manifest themselves to it directly, if and only if they have charges If they do not have charges they must induce charged particles to manifest them vicariously. "Induce" is after all a pretty weak word for the process in question, which is more like assault than it is like persuasion. The liberated neutron, rushing at high speed through space, happens to strike a forcible blow against an atom-nucleus, preferably a proton This struck particle recoils from the impact, and being charged is able to manifest itself to us through our apparatus Anyone who has travelled in France has probably noticed that the verb *inviter* has a somewhat different flavor from our supposedly-equivalent *invite*, for one reads (for instance) that a crowd assembled in a place where it was not desired, and the policeman came and *invita* its members to go elsewhere It is in this sense that the free neutron, happening to be advancing straight toward a nucleus, invites the latter to go elsewhere I do not play billiards, which is certainly a defect in a person who must refer to billiard-balls as often as a physicist does, but I have at least looked upon billiard-tables, and I have noticed that sometimes there are balls of two different colors Suppose that on the table there were, not white balls and red balls, but white balls and invisible balls Conceivably one might infer the presence of the invisible balls, by noticing that every now and then one of the white balls started off at a great speed without any visible cause. Of course somebody might conclude the existence of invisible players instead of invisible balls, but that would be an animistic way to look at the situation instead of a scientific way. In Nature—that is to say, in our apparatus—the neutrons correspond to the invisible balls, the nuclei to the white ones We know of the free neutrons, because every now and then one of the nuclei will start off in precipitate flight. There is another way of detecting the neutrons, depending on the fact that when they impinge on nuclei of certain kinds they enter these and cause them to explode· the flying fragments of these explosions are observable because and only because they are charged, and so we come back to the same techniques.

Now I must say that the neutron is not the first-to-be-discovered of *all* neutral particles, but only the first-to-be-discovered of those which have the quality of matter The earliest-to-be-discovered of all the fundamental neutral particles are the corpuscles of light, the photons. The individual photon seems to be just as powerless as the individual neutron to manifest itself to us directly It has to invite a charged particle for the purpose, and to strike it a blow—or, to use a gentler and more technical phrase, it has to confer some of its own energy on the charged particle. Whereas the invitations of neutrons are directed to nuclei, those of the corpuscles of light are addressed to electrons. There are interactions of various kinds between electrons and photons, and for one at least among them it is permissible to use that image of the colliding billiard-balls Let me now add that when a physicist speaks of billiard-balls, he is using a metaphor for what in a professional paper he would call "strong short-range forces." These forces are non-electrical, or at any rate if we were to call them electrical we should be distorting the word out of sense.

But how about the possibility that these neutral particles may be, each of them, a pair of charged corpuscles locked so tightly into each other's arms that to the outside world their charges seem totally annulled while yet remaining distinct?

At first glance this appears to offer a chance of saving or reviving the electrical theory of matter Not so much can be expected of it, since now and henceforward the short-range or billiard-ball forces must be implanted in every conception of either charged or chargeless particles Little or nothing would be gained by trying in imagination to link chargelessness with charge, were it not for some quite remarkable phenomena which more than justify the attempt The most striking of these are the conversion of individual photons into pairs of free electrons, one member of the pair being negative and the other positive, and the conversion of electron-pairs into photons Though known for barely four years as yet, both of these phenomena have been detected many times over in many ways, and while the experiments still want the last refinements of accurate measurement, there is no reasonable doubt remaining. Now, no one maintains that a corpuscle of light is nothing but a pair of electrons close together There are too many objections to such a simple idea, anyone can think of several, I will mention only that light in vacuo is constrained to a single definite immutable speed and electrons suffer from no such limitation The most that here can be asserted is, that equal and opposite charges come out of apparent chargelessness, and equal and opposite charges return into apparent chargelessness, and other remarkable changes occur at the same time.

Do equal and opposite charges ever come out of the neutron, and do equal and opposite charges ever meet and form a neutron in disappearing? Nothing of the kind has yet been observed, and there is in fact a strong reason for disbelieving in the quite obvious idea that a neutron may be a proton and a negative electron tightly clasped together.

Nevertheless there is the disconcerting fact that electrons are observed to spring out of nuclei—out of more than two hundred different kinds of "radioactive" nuclei I call it disconcerting, because I have been trying to make you picture every nucleus as a composite of nothing but protons and neutrons, and here I suddenly burst out with the admission that these alleged composites of protons and neutrons are perfectly capable of projecting free electrons into the outside world! I must further confess that this very affair of the ejection of negative electrons from nuclei was precisely one of the reasons that made people prefer the more complicated nucleus-model which I invited you to reject, over the simpler one which I recommended you to accept Admittedly I was not being fair to the complicated model However the chances are that I was not misleading you The people of the days before 1932 who believed in the proton-and-negative-electron model of the nucleus did not know nearly so much about the variety of Nature as they were soon to learn They did not know that neutrons can be detached from nuclei, or that some radioactive nuclei emit electrons which are positive instead of negative So, if one insists on putting into the nuclear zoo at least one specimen of every kind of animal which has been observed to come out—if one insists upon that, then one has to make a model containing at the very least four kinds of fundamental particles neutrons, protons, electrons of both signs This is so complicated a prospect, that of late the theorists have been trying out the alternative idea the idea that the electrons which are fired out of radioactive nuclei are created just before they depart. It is conjectured that the neutron in the nucleus may possess the power of converting itself into an electron of either sign, and a residue which would either be a proton, or a particle equal in mass but opposite in sign of charge to the proton.

I do not guarantee these ideas—not that my guarantee, or the lack of it, would make the slightest difference to their proponents—and I certainly do not present them to you on the same footing as the conversion of photons into electron-pairs. This is a fact of experience, and an addition to knowledge, those are illustrations of the trend of thought All of them anyhow illustrate my point that the neutral particles and the non-electrical forces have come back into physics after their exile of nigh on forty years, and that we have both the fact and the speculation of electric charge coming into being out of neutral mother-substance and returning into it again. Of course this may be a very transitory stage in modern physics. However at least for the present we may feel assured that even the wisest of theorists would not dare to debar us from contriving a cosmos in which neutral particles exist as well as charged ones, non-electrical forces as well as electrical, and perhaps even charge is secondary and a neutral mother-substance primary

THE MAP OF LATIN AMERICA BY TREATY

S WHITTEMORE BOGGS

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(Communicated by Waldo G Leland)

(*Read, April 22, 1938*)

ABSTRACT

The historical materials for the study of Latin American boundaries are widely scattered, in publications of many countries, and in several languages They are difficult to find, and to use when found Overlapping claims involving three or more countries have made the boundary disputes and negotiations surprisingly complex For these reasons, and because of the unusual importance of boundary questions in Latin American history, scholars, writers and statesmen are seriously handicapped by the lack of a compilation analogous to Hertslet's "Map of Europe by Treaty"

To illustrate the problems involved, the history of overlapping claims of Brazil, Ecuador, Colombia and Peru is reviewed Problems derived from inadequate geographical knowledge are illustrated from old maps of the Honduras-Nicaragua area

A comprehensive study of Latin American boundaries seems to require two publications:

(1) "The Map of Latin America by Treaty," containing the texts of papal bulls, treaties of the colonial and republican periods, arbitral awards, etc, arranged chronologically, each in the original language with English translation, each accompanied by explanatory notes, many by maps

(2) "A History of Latin American Boundaries," containing the history of the establishment of each of the 38 boundaries from the Rio Grande southward

As the first step, a pamphlet should be prepared containing

I A chronological list of documents contemplated in "The Map of Latin America by Treaty"
II A classified list of the same documents arranged by country and by individual boundary
III A bibliography of treaty collections, etc

The library resources of Washington are probably unexcelled for such a study The map of Hispanic America prepared by the American Geographical Society of New York affords an excellent cartographic base

THE historical materials in which the successive stages of the development of international boundaries of Latin America are recorded are widely scattered in publications of the twenty

Latin American republics, Spain, Portugal, Great Britain, France, the Netherlands, and the United States. They are difficult to find, and perhaps equally difficult to use when brought together. Overlapping claims of three or four countries within a single area account for interrelationships between bilateral boundary disputes and negotiations which are surprisingly numerous and complex. In the words of an eminent authority

> . It may be said that a very considerable part of the diplomatic history of Latin-America reduces itself to an account of the struggle over boundaries For this reason, and because of their great political and economic significance, these contests occupy a place of capital importance in that history [1]

It may therefore be appreciated that scholars, writers and statesmen are seriously handicapped by the lack of any compilation relating to boundaries in the Americas which is analogous to Hertslet's "Map of Europe by Treaty" or Hertslet's "Map of Africa by Treaty."

The Latin American republics, throughout more than a century of independence, have undertaken generally to establish their boundaries on the principle of *uti possidetis*, that is, on the basis of the extent, at the time they established their independence, of the territory possessed by the several viceroyalties, captaincies-general and other entities from which they evolved as independent sovereign states. The natural tendency has been for each country to apply this principle in a manner that would give it a maximum domain A long series of boundary disputes, of which several are even now unsolved, may be traced to vaguely defined limits of administrative and ecclesiastical divisions in poorly mapped areas, and to numerous transfers of territory from one colonial jurisdiction to another.

Some of the problems involved in considering the boundaries in Latin America may be illustrated in a region in which four of the ten South American republics meet, namely

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[1] John Bassett Moore Memorandum on uti possidetis, Costa Rica-Panama arbitration (1913), pp 14–15.

Brazil, Ecuador, Colombia and Peru In an area of widely overlapping claims, each of four such countries may have a dispute with each of the three other neighbors, the six pairs of countries thus afford six boundary disputes. But with four countries situated as these are (no one of them being surrounded, as is Bolivia or Paraguay), there could not possibly be six boundaries Once the disputes were disposed of, one of the six must have been pinched out, leaving five actual frontiers between the four countries.

As the boundaries have become established the possibility of a boundary between Brazil and Ecuador has been eliminated. The other five have become actualities, including the undefined Ecuador-Peru frontier

At the risk of over-simplification, these six boundary controversies will be sketched, illustrated by lantern slides

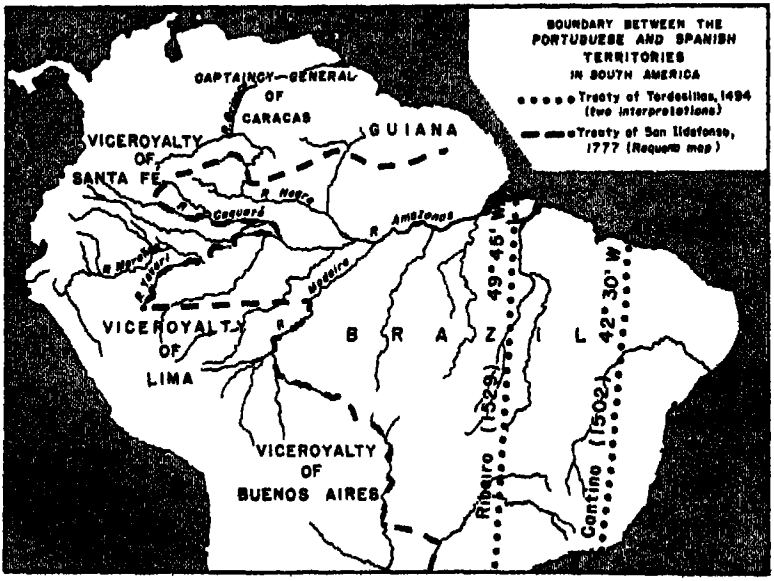
BOUNDARY BETWEEN THE PORTUGUESE AND SPANISH TERRITORIES IN SOUTH AMERICA
Treaty of Tordesillas, 1494 (two interpretations)
Treaty of San Ildefonso, 1777 (Requena map)
CAPTAINCY—GENERAL OF CARACAS
VICEROYALTY OF SANTA FE
GUIANA
R. Negro
R. Caquetá
R. Amazonas
R. Madeira
R.
VICEROYALTY OF LIMA
VICEROYALTY OF BUENOS AIRES
B R A Z I L
49° 45' W
42° 30' W
Ribeiro (1529)
Cantino (1502)

FIG 1

The boundaries of Brazil, as you are aware, are based in general upon the line separating the territories of the Crowns of Portugal and Spain at the time when it became independent, in 1821. The line of the treaty of Tordesillas, 1494, a meridian 370 geographical leagues west of the Cape Verde Islands could not be located accurately at that time, because of uncertainties regarding the initial point in the Cape Verde Islands, the extent of a geographical league in relation to the circumference of the earth, and the impossibility of determining longitude reliably at sea until well more than a century later. The Tordesillas line gave Portugal a foothold in Brazil Two of the early attempts to lay down the Tordesillas line [1] are shown on Fig 1 The longitude difference between the two meridians is greater than that between Philadelphia and Cleveland.

The treaty of Madrid, 1750, and the treaty of San Ildefonso, 1777, made at least a preliminary attempt to delimit a Portuguese-Spanish boundary The San Ildefonso line, as represented on the map made by Francisco Requena,[2] 1796, is shown on Fig 1 The viceroyalties of Santa Fé, Lima and Buenos Aires, and the captaincy-general of Caracas, as shown on the Requena map without boundaries, are likewise indicated

On the maps that follow it will be shown that all four countries have claimed territory between the Caquetá or Yapurá and the Amazon, and that at least three countries have claimed territory north of the Caquetá To the triangular controversies between Venezuela, Brazil and Colombia, and likewise between Bolivia, Brazil and Peru in the Acre region, we shall make only passing reference

As a background for a brief review of the disputes between the four republics, Fig. 2 shows the boundaries as they are today, in part by means of distinctive shadings. All of them within the area of the map are now established except that between Ecuador and Peru

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[1] Henry Harrisse The Diplomatic History of America Its First Chapter, 1452-1493-1494 London, 1897 Map facing title-page

[2] "Mapa geográfico de la mayor parte de la América Meridional que contiene los paises por donde debe trazarse la linea divisoria que divida los dominios de España y Portugal, construida en virtud de Real Órden por el Teniente General D^{n} Francisco Requena en el año de 1796 Printed by F Bourquin, 31 So Sixth St, Philadelphia, Pa"

In its various boundary disputes, Colombia has in general based its territorial claims upon the extent of the viceroyalty of Santa Fé or New Granada, according to royal cédulas of 1717 and 1739, minus the audiencia of Quito Ecuador has claimed the territory of the audiencia of Quito, created in 1563, belonging alternately to the viceroyalties of New Granada and Lima Peru has in general claimed the territory of the viceroyalty of Lima or Peru, citing early cédulas and also one of 1802 which enlarged its borders shortly before independence Brazil, as has already been indicated, has claimed territory based chiefly on the extent of Portuguese possession in 1821, but it has sometimes maintained that subsequent effective occupation of portions of the upper Amazon basin was consistent with the *uti possidetis* principle.

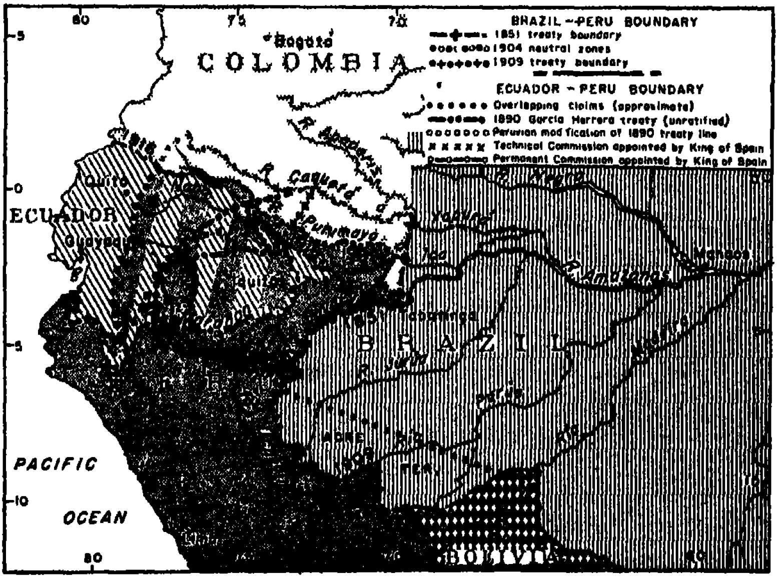

FIG 2

BRAZIL-PERU BOUNDARY

Brazil and Peru by treaty in 1851 defined their boundary as constituting the straight line from the mouth of the

Apaporis River in the Caquetá, to Tabatinga on the Amazon (we shall necessarily hear more of this Apaporis-Tabatinga line), and from Tabatinga southward, the Javary River to its source (Fig 2). Colombia immediately protested, denying the right of both Brazil and Peru to the territory traversed by the Apaporis-Tabatinga line. A minor modification was made in 1874, where the line cuts the Putumayo The Bolivia-Brazil dispute in the Acre area having been settled by treaty in 1903, Peru and Brazil in 1904 established neutral territories in the upper Juruá and Purús river basins In 1909 they extended their boundary from the source of the Javary to the point where their respective frontiers with Bolivia begin.

ECUADOR-PERU BOUNDARY

Ecuador and Peru made several attempts to establish their common boundary, beginning in 1832. However, no treaty between them has ever gone into effect which defined any portion of their frontier. The Garcia-Herrera Treaty of 1890 defined the entire boundary, from the Apaporis-Tabatinga line to the Pacific Ocean. Ecuador ratified it; Peru ratified it with territorial modifications which Ecuador rejected Colombia objected to the proposed settlement, and a tripartite convention was negotiated in 1894, which was never perfected by the exchange of ratifications.

Fig 2 shows approximately the area in dispute, totaling 40,000 or 45,000 square miles—the area with alternate shadings characteristic of Ecuador and Peru, partially surrounded by a line of large heavy dots. A larger area formerly claimed by the two countries is indicated by the similar line of smaller dots. The maximum former claims of Ecuador and Peru in their dispute have included much that is now in Colombia, and part of Brazil. The area once claimed by Peru included Guayaquil The Garcia-Herrera Treaty line, with the Peruvian modification, and the lines of the two Commissions appointed by the King of Spain, are shown running through the disputed area.

In the arbitration before the King of Spain, under the treaty of 1887, Ecuador claimed the ancient boundary between the viceroyalties of New Granada and Peru, based on the cédulas of 1717 and 1739, that is, at the time of the creation of New Granada. Peru claimed the boundary between the same viceroyalties based in part upon a royal cédula of 1802.

Under the terms of a protocol of 1924 delegations of the two countries have been negotiating in Washington since 1936, but thus far have not succeeded in reaching an agreement on the boundary

BRAZIL-ECUADOR BOUNDARY

Brazil and Ecuador by treaty in 1904 agreed that if the Ecuador-Peru boundary dispute were settled in favor of Ecuador the Brazil-Ecuador boundary should be, wholly or in part, the Apaporis-Tabatinga line defined by Brazil's treaties of 1851 and 1874 with Peru The treaty further declared that the two high contracting parties had no intention of prejudicing the rights that might be subsequently established by neighboring countries, referring specifically to the boundary question between Brazil and Colombia, and to the triangular questions between Ecuador, Colombia and Peru. Subsequent developments may be said to have pinched off Ecuador some distance to the west of the Apaporis-Tabatinga line, Colombia and Peru intervening and thus excluding the possibility of Ecuador and Brazil being contiguous states.

COLOMBIA-ECUADOR BOUNDARY

Colombia and Ecuador made several attempts to establish their frontier, beginning with a treaty of peace and friendship in 1832. The treaty of 1916, however, is the only treaty that ever went into effect between Colombia and Ecuador that defines any portion of their common frontier (Fig. 3). The entire boundary was defined from the Pacific Ocean to the Marañon or Amazon River. A considerable portion of it has since been demarcated.

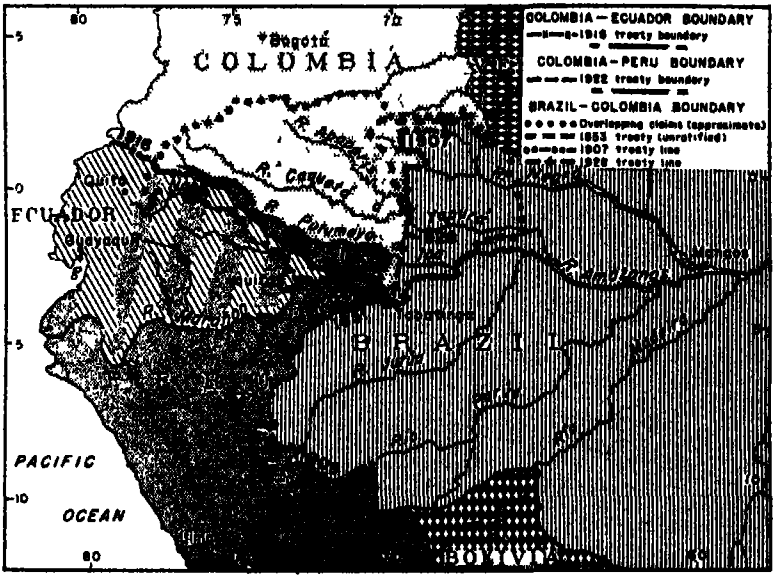

Fig 3

About two-thirds of the boundary has been eliminated as a frontier between Colombia and Ecuador, by the Colombian cession of a long strip of territory to Peru

Colombia-Peru Boundary

The Colombia-Peru boundary was defined by treaty in 1922, ratifications being exchanged in 1928 It will be observed (Fig 3) that much of the line lies to the north of the Colombia-Ecuador 1916 boundary. Colombia conceded to Peru, therefore, a long, narrow strip of territory which Ecuador had previously conceded to Colombia, lying south of the Putumayo River, and north of the Putumayo-Napo divide Ecuador had agreed to the Putumayo as its boundary with Peru, by the Garcia-Herrera treaty, on the assumption that Ecuador rather than Colombia would be sovereign of the territory north of the Putumayo By the 1922 treaty with Colombia, Peru now surrounds on three sides territory that is claimed by Ecuador

By the same treaty Colombia acquired a corridor to the Amazon River immediately to the west of the Apaporis-Tabatinga line—the so-called Leticia quadrilateral Colombia furthermore reserved its right to claim territory to the east of the Apaporis-Tabatinga line which Brazil had regarded as having been established as Brazilian territory by its treaties of 1851 and 1904 with Peru and Ecuador respectively To this disconcerting provision Brazil objected A triangular dispute arose between Brazil, Colombia and Peru which remained unsettled until the Gordian knot was cut by the protocol of Washington, signed March 4, 1925 The terms of that protocol have now all been carried out, in three bilateral negotiations between the three pairs of countries

BRAZIL-COLOMBIA BOUNDARY

The maximum area formerly in dispute between Brazil and Colombia is shown on Fig 3 by the line of heavy dots An unratified treaty of 1853, when geographical knowledge was very deficient, would have provided a boundary line approximately like the double line of dashes on Fig 3

The northern triple point with Venezuela is in an area that was in dispute between the three countries for nearly a century after independence, the Colombia-Venezuela boundary was determined by arbitration in 1891 From the point common with Venezuela, a 1907 treaty fixed the Brazil-Colombia boundary to the mouth of the Apaporis. The remainder of the boundary was left undecided, pending settlement of Colombia's disputes with Ecuador and Peru. Both of the latter having been subsequently settled, in 1928 the Brazil-Colombia boundary was extended southward by the Apaporis-Tabatinga line to the Amazon That line has therefore served successively as Brazil's boundary with Peru (1851), Ecuador (1904, provisionally) and now Colombia (1928).

The complexities of each of the six preceding controversies are much greater than it has been possible to indicate in this brief summary.

HONDURAS-NICARAGUA BOUNDARY

Another factor that confuses the student of Latin American boundaries is the wide divergence in maps, owing largely to the lack of surveying and mapping in large areas over a long period of time.

An illustration is afforded in the area of the former dispute between Honduras and Nicaragua. Fig. 4 shows the claims of the two countries as they were presented to the arbitrator, the King of Spain. The Segovia and the Patuca rivers, which the claims followed in large part, are shown here as they appear on the millionth sheet compiled and published by the American Geographical Society of New York; these are the river courses which are followed by the symbols which are explained in the legend, on which the river names are shown

On this map the courses of the Segovia and Patuca rivers have been added as they appeared on four of the maps which

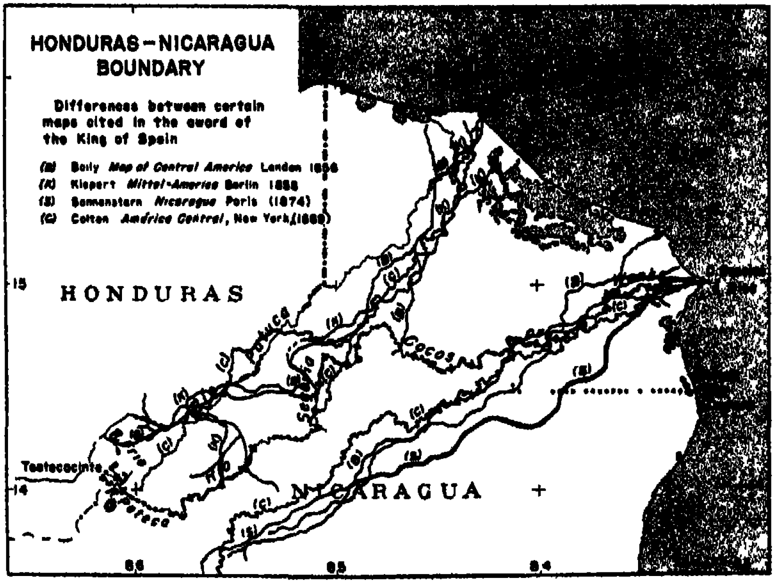
HONDURAS-NICARAGUA BOUNDARY
Differences between certain maps cited in the award of the King of Spain
(B) Baily *Map of Central America* London 1856
(K) Kiepert *Mittel-America* Berlin 1858
(S) Sonnenstern *Nicaragua* Paris (1874)
(C) Colton *América Central*, New York (1866)
HONDURAS
NICARAGUA
Patuca
Segovia
Cocos
Teotecacinte
Poteca
15
14
86
85
84

Fig. 4.

are cited in the award of the King of Spain December 23, 1906. They have, of course, been replotted on the same projection and scale. It is not difficult to imagine the confusion that would have resulted if more of the maps which were cited by the two parties to the dispute had been similarly reproduced.

A Comprehensive Plan of Study

These illustrations of problems to be faced in the study of Latin American boundaries are perhaps sufficient to indicate that there is here an ample supply of chaos from which to create a considerable world of order

On the map of the Americas there are now 29 boundaries between Latin American republics, and 6 boundaries between a Latin American country on the one side and the United States, the Canal Zone, or a European colony on the other. There are two more boundaries between European colonies in the Guianas No comprehensive bibliography on Latin American boundaries has been prepared. Mention should be made of a recent book on South American boundaries by Gordon Ireland.[1] An impartial, systematic history of all the boundaries in Latin America is much to be desired.

An adequate project relating to the history of Latin American boundaries would seem to require two publications

(1) "The Map of Latin America by Treaty," a series of probably three to five volumes, containing the texts of papal bulls, Portuguese-Spanish treaties, Spanish cédulas, treaties between Latin American republics, and arbitral awards Documents to be arranged chronologically, each in the original languages, with English translation, each to be followed by brief notes indicating its bearing on related boundary developments. Important documents to be accompanied by maps.

(2) "A History of Latin American Boundaries," probably in one volume, containing the history of each of the thirty-eight boundaries from the Rio Grande southward (including

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[1] Gordon Ireland Boundaries, Possessions and Conflicts in South America, Harvard University Press (1937), p 126.

the provisional Brazil-Ecuador boundary, now eliminated). The boundary history of the colonial period should be given in so far as it is essential to a study of the present international boundaries and pending disputes

The first step might well be the compilation of a list of documents which should be published and used in these two closely related publications This list of documents might be published in a pamphlet of perhaps 80 to 100 pages, which would contain the following

I. A chronological list of documents (papal bulls, cédulas, órdenes, treaties, arbitral awards, etc), the publication of which is contemplated in "The Map of Latin America by Treaty"

II A classified list of the same documents, arranged by countries, and by individual boundaries (*e g* , Brazil-Colombia boundary)

III A bibliography of the treaty collections, etc , in which the larger part of the documents may be found The bibliography should also include the more important maps, and works by individual scholars on specific boundaries

Such a pamphlet would itself be highly useful pending the completion of definitive publications The preparation of copy, editing, and publication of this preliminary pamphlet would probably require a year or more of research and study, and at the same time would accumulate considerable material *for immediate use in the work on the major publications*

The library resources of Washington are probably unexcelled for this study—the Library of Congress, the Pan American Union, the Department of State, the Catholic University, and other collections The map of Hispanic America in the scale of 1 1,000,000, nearly completed, prepared by the American Geographical Society of New York, affords an excellent cartographic base

MATING TYPES IN PARAMECIUM AURELIA: DIVERSE CONDITIONS FOR MATING IN DIFFERENT STOCKS; OCCURRENCE, NUMBER AND INTERRELATIONS OF THE TYPES[1]

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(Communicated by H. S. Jennings)

ABSTRACT

Mating types have been found in four species of Paramecium, in addition to the two previously reported in *P. trichium* and *P. calkinsi*, by Sonneborn, and in *P. multimicronucleatum* and *P. caudatum*, by Gilman and by Giese and Arkoosh.

Analysis of 26 stocks of *P. aurelia*, collected between North Carolina and Massachusetts and in California, shows that they are divisible into three groups, each of which consists of two mating types. Any member of one of the two types will conjugate with any member of the other, but not ordinarily with a member of its own type. The two types of group 1 are designated I and II, those of group 2 are types III and IV, those of group 3 are types V and VI. Group 1 includes 9 of the stocks, five of these (all from one source) consist exclusively of mating type I, each of the other four (from diverse sources) contains both types I and II. Group 2 includes 13 of the stocks (from diverse sources), 12 of them contain mating types III and IV, the other one has yielded type IV only. These two types give the characteristic clumping reaction and conjugate when mixed at night or early morning at temperatures not exceeding 25° C., best at 17° to 19° C. The percentage of conjugation obtained depends upon the temperature both before and during mixture of the types. Group 3 includes three of the stocks (from diverse sources), each of these contains mating types V and VI. These react and conjugate between 1 A.M. and 1 P.M. at temperatures not exceeding 27° C. Their diurnal periodicity in reactivity is a consequence of the alternation of light and darkness, visible light suppressing reactivity.

Mating types appear to be of universal occurrence in *P. aurelia*, "non-conjugating" or rarely conjugating stocks seem not to exist. Some stocks appear, however, to consist exclusively of one type, and in order to get these to conjugate, they must be mixed with the appropriate type from another stock.

A weak clumping reaction, never followed by conjugation, regularly occurs under favorable conditions in mixtures of types II and V. Hence, types I and V are similar in that both react with type II, and types II and VI are similar in that both react with type V. This suggests that these two pairs of types, and possibly all three pairs, may have originated as modifications of a single original pair of types.

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[1] Aided by a grant from the Penrose Fund of the American Philosophical Society.

[2] The experimental work was carried on with the technical assistance of Miss Mildred Musher.

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IN *Paramecium aurelia*, there have been found (Sonneborn, 1937) two types of individuals and cultures that immediately form clumps when brought together From these clumps, the individuals later emerge paired in conjugation, each pair consisting of one individual of one type and one of the other As conjugation is a normal consequence of the clumping reaction and as conjugation takes place usually or only between individuals of diverse types, these types will be referred to as mating types

Although the mating types are definite and the reaction between them striking, they had not been found in any of the many previous investigations on conjugation of *Paramecium* and other comparable ciliates Does this mean that they are exceptional and of rare occurrence? On this question evidence is at present available only for the genus *Paramecium*. Mating types have been reported in two species, in *P aurelia* by Sonneborn (1937) and in *P. bursaria* by Jennings (1938a) I can now report that similar types occur in two other species, *P. trichium* and *P. calkinsi* Mr Lauren Gilman of this laboratory, and Giese and Arkoosh of Stanford University permit me to state that they have found them in two more species, *P multimicronucleatum* and *P. caudatum* We have thus far found no species of *Paramecium* in which mating types are absent

There is however a further question concerning the universality of such types In species in which they have been found, do they occur in all stocks or only in some? According to the published reports on both *P aurelia* and *P bursaria*, mating types were found in some stocks and not in others. Do the latter actually lack them? In *P aurelia*, the clue to the solution of this problem was the discovery that the species contains three kinds of stocks differing in the conditions required to bring about conjugation An account of this will be given in the first part of this paper.

With this knowledge, the question of the universal occurrence of mating types in *P. aurelia* was investigated by examining 26 diverse stocks, including those in which such types were earlier not found As will appear in the second part of this paper, each of these stocks was found to consist of one or two mating types.

In order to ascertain how many *diverse* mating types exist and how they are interrelated, the 32 types found in 17 of the stocks were mixed together two at a time in all possible combinations The results show that the 32 types are reducible to only six diverse ones The remaining nine stocks were analyzed less extensively, but sufficiently to show that they consist of types identical with those in the stocks examined more fully With respect to the types they contain, the 26 stocks are divisible into three groups, each group containing but two of the types Conjugation occurs only between the two types in the same group, not between types in different groups Nevertheless, one combination of types from different groups yields regularly a weak clumping or mating reaction, this suggests that of the six types, three may be diverse modifications of one type, three diverse modifications of another The studies on the number and interrelations of the mating types are dealt with in the third part of this paper. Finally, the phenomena of mating types and sexuality in diverse unicellular organisms are compared and the relation of the types to sexuality is discussed

Material Each of the 26 stocks consists of the descendants of a single individual A list of the stocks and their sources follows Stock A from Strickersville, N. Y , stocks B, F, N, O, P, T, U, V, and X from a stream in Woodstock, Md , stocks C, J, K, M, Q, and R from different ponds in Baltimore, Md , stock D from Counterfeiter's Lodge, N. Y , stock E from Elkridge, Md , stock G from near Pinehurst, N. C , stock H from Halethorpe, Md , stock I from near Buffalo, N. Y , stock L from Staunton, Va., stock S from Cold Spring Harbor, N. Y., stock W from Williamstown, Mass., stock Y from near Cockeysville, Md., and stock Z from Stanford, California For some of these stocks I am indebted to Professors H S. Jennings, L. L Woodruff and A. A. Schaeffer, to Drs. Coleen Fowler, R Wichterman, D Raffel, and A. C

Giese, to Fathers J A Frisch and C. A. Berger, S. J.; and to Messrs. N. Finklestein and C W. Metz, Jr.

I. THE CONDITIONS REQUIRED TO BRING ABOUT THE MATING REACTION AND CONJUGATION IN DIVERSE STOCKS OF PARAMECIUM AURELIA

With respect to the conditions required to bring about the mating reaction and conjugation, there are certain general rules that hold for all of the 26 stocks investigated. The first and most important one is that animals of appropriate different mating types must be brought together. The evidence for this will be given in the following section of this paper Another general rule is that the individuals must not be overfed Finally, in order to react, they must not be undergoing fission, endomixis or conjugation. In addition to these general rules, there is one that holds for a number of stocks, namely, that during the first six to ten days after conjugation the mating reaction and conjugation will not occur, but in other stocks, this period of "immaturity" is either entirely lacking or so brief as to escape detection. The existence of a period of immaturity has thus far not been correlated with any other characteristic of these stocks.

For one group of stocks (stocks B, F, J, N, O, P, R, S, T, and Z), no additional special conditions need be fulfilled in order to bring about the mating reaction and conjugation; but the remaining stocks are divisible into two groups each requiring its own particular conditions. Both groups react and conjugate only at certain hours and under certain temperature conditions, the hours and temperatures being somewhat different for the two groups.

One group, including the stocks A, C, D, E, G, H, I, K, L, U, V, W, and X, reacts best between 17° and 19° C., and not at all above 25° C. The percentages of conjugants appearing in mixtures of opposite mating types kept separately for one day and then mixed at the same temperature were 4 per cent at 9°, 68 per cent at 17.6°, 53 per cent at 18.6°, none at 24.5° or 32.2° C. Moreover, as shown in Table 1, the temperature

TABLE 1

THE NUMBER OF PAIRS OF CONJUGANTS FORMED IN MIXTURES OF 100 ANIMALS OF EACH OF THE TWO MATING TYPES IN STOCK K (GROUP 2)

		Temperature after Mixture of the Two Types				
		9.0°±0.2°	17.6°±0.2°	18.6°±0.4°	24.5°±0.5°	32.2°±0.5°
Temperature *for one day* before mixture	9.0°±0.2°	4	78	89	14	0
	17.6°±0.2°	14	68	72	15	0
	18.6°±0.4°	30	44	53	1	0
	24.5°±0.5°	14	36	43	0	0
	32.2°±0.5°	7	25	26	6	0

before mixture of the types, as well as the temperature after mixture, is important. The highest percentage of conjugants (89 per cent) appeared in cultures mixed at 18.6° after a preliminary day unmixed at 9° C. However, as this procedure takes three days to obtain conjugation, another more rapid technique was usually employed. The mating types were cultivated separately at 20° to 27° C., then mixed and put directly at 17° to 19° C. With this method, conjugants are ordinarily found the first morning after mixture.

When the proper temperature conditions are fulfilled, the stocks of this group give the mating reaction when opposite types are mixed at certain hours, but not when mixed at other hours. A weak mating reaction may be obtained as early as 6 P.M., though usually not until 9 or 10 P.M. Weak reactions may be obtained as late as 9 or 10 A.M., but usually not later than 7 A.M. When mixtures were made hourly throughout the night, the best immediate reactions took place between 1 A.M. and 5 A.M. The period of optimum reactivity varies by a few hours in different experiments, but it always occurs at hours so unfavorable for full investigation that I cannot claim to have analyzed this subject exhaustively. For all practical purposes it is sufficient to mix opposite types during the day and put them at 17° to 19° C. Conjugation then begins during the night or early morning and, as pairs remain together more than 12 hours at these temperatures, the conjugants are found when the cultures are examined during the morning In all cases where exhaustive study is required, such mixtures are examined night and morning at 12 hour intervals for two or three days

The remaining group of stocks, including stocks M, Q, and Y, react at somewhat higher temperatures Excellent reactions occur up to 24° and weaker ones up to 27°, but none at 30° C. Furthermore, the diurnal periodicity in this group is markedly different from that in the preceding group The reactive period does not begin until 1 A M. and then only feebly, and it stops completely in the early afternoon, usually before 1 P M The period of optimum reactivity is between 4 A.M. and 11 A M

With stock Q of this group, an attempt was made to discover the leading factor involved in the diurnal periodicity. As might be supposed, this factor is the daily alternation of light and darkness. Cultures kept continuously in the dark gradually start reacting earlier in the night and continue later in the day After five days of continuous darkness, they react with equal readiness at all hours of the day and night The opposite occurs with cultures kept illuminated continuously (For this purpose, there was used an effective illumination of about 100 foot-candles from a water cooled 200 watt hygrade bulb, using as an infra-red filter a 1 cm cell of N/2 copper chloride) The reactive period gradually shortens and the reactions decrease in intensity until, after five days of continuous illumination, no further reactions occurred at any hour of the day or night In order to ascertain whether the effective action was a stimulation by darkness, seven series of cultures were put into darkness at each hour from noon until 6 P M Beginning at 10 P.M and continuing hourly thereafter, two cultures (one of each type) from each series were mixed together. None reacted until 1 A.M., and all began reacting at about the same time regardless of when they had been put in the dark Apparently darkness does not stimulate reactivity. In order to test the alternative possibility, suppression of reactivity by light, similar series of cultures were all put into darkness at 5 P M and withdrawn and tested at successive hours the following day. As appears in Table 2, the later in the day the cultures were first exposed to daylight, the later they continued to react For example, the culture first exposed at 2.20 P M was still reacting strongly after the one exposed at 9 20 A M. had completely stopped reacting, and the culture exposed at 5 05 P M. reacted weakly four hours after the last weak reaction of the culture exposed at 9 20 A.M Thus the ordinary daily periodicity in reactivity appears to be due primarily to the suppressing effect of light

TABLE 2

THE RELATION BETWEEN TIME OF FIRST EXPOSURE TO DAYLIGHT AND TIME OF CESSATION OF MATING REACTIVITY IN STOCK Q (GROUP 3) OF *P aurelia*

Strong reaction denotes that 50 per cent to 100 per cent of the animals clumped, weak reaction denotes that the clumps included less than 50 per cent of the animals, negative test denotes that no clumping occurred at all Cultures of the two mating types were brought into the light from darkness at each hour of the day and each of these was tested hourly thereafter until reactivity ceased

Time of First Exposure to Light	Time of Last Strong Reaction	Time of Last Weak Reaction	Time of First Negative Test
8 30 A M	12 45 P M	1 51 P M	2 40 P M
9 20 A M	12 47 P M	1 48 P M	2 42 P M
10 15 A M	12 49 P M	2 52 P M	3 30 P M
11 16 A M	1 50 P M	2 50 P M	3 32 P M
12 25 P M	1 25 P M	3 45 P M	4 25 P M
1 25 P M	2 20 P M	—	3 40 P M
2 20 P M	2 45 P M	4 05 P M	4 18 P M
3 17 P M	—	3 47 P M	4 15 P M
4 15 P M	—	4 48 P M	5 15 P M
5 05 P M	—	5 45 P M	—

The foregoing account of the conditions required for the mating reaction and conjugation in the three diverse groups of stocks is intended to be little more than a portrayal of the conditions that must be fulfilled in order to carry out successfully investigations of the mating types. Further investigation would doubtless reveal factors influencing reactivity other than those here set forth

II. THE UNIVERSAL OCCURRENCE OF MATING TYPES IN PARAMECIUM AURELIA

To investigate the universality of occurrence of mating types in *P aurelia*, 17 of the 26 stocks were analyzed exhaustively and the other nine less fully, but adequately The methods employed were based on the knowledge set forth in my earlier paper (Sonneborn, 1937), that in stock S the progeny produced by fissions of a single individual are all of the same mating type so long as neither endomixis nor conjugation intervenes, but that at the first fission of an exconjugant the two types, I and II, often segregate. Kimball (1937) found that these types may also segregate at the first fission after the climax of endomixis. Therefore, every culture used in the study of mating types consisted of the vegetative progeny of a single individual produced at least one fission after an endomixis or conjugation. Such cultures include only individuals containing macronuclei descended by division from a single original macronucleus, for each exconjugant and endomictic individual forms two macronuclear anlagen that segregate at the first fission As the individuals containing macronuclei descended from a single macronucleus are ordinarily alike in mating type, it will be convenient to introduce the term *caryonide* to denote them. A caryonide thus consists of an individual containing but one of the macronuclear anlagen formed at conjugation or endomixis and all its progeny produced until another nuclear reorganization takes place. In the rare cases when more than two macronuclear anlagen are formed at these processes, the caryonides arise at a fission slightly later than the first.

For exhaustive analysis of a stock, the method was to obtain a number of exendomictic or exconjugant caryonides and mix together samples of these in all possible combinations of two. Each mixture was then observed for the mating reaction and conjugation. If these occurred, the cultures mixed were of different mating types Among the stocks examined in this way, there were two (stocks B and W) in which none of the mixtures reacted or yielded conjugants; these results and their significance will be taken up later In the remaining stocks, some of the mixtures yielded conjugants and others did not. In each of these stocks, however, the results fell into the same kind of definite system, as will now be set forth As examples of the relations found, there will be given the results on one stock from each of the three groups differing in the conditions required for the mating reaction, for as will appear later, these groups also differ in the mating types they contain

In group 1, in which the mating reaction occurs at any time of the day or night, the relations in stocks R and S have to some extent been reported previously (Sonneborn, 1937, 1938), stock F will be employed here as an example of the results with this group Eleven different exconjugant caryonides were mixed in all possible combinations of two with the results shown in Table 3, where the symbol in each square indicates whether the mating reaction and conjugation occurred in mixture of the caryonides on the corresponding row and file. The symbol – indicates that no reaction or conjugation occurred, the symbol + that they did As appears on one of the diagonals of the table, no conjugation occurred in any mixture of two cultures of the same caryonide Among the 55 different possible mixtures of two caryonides, conjugation occurred in 30, but not in the other 25. The mixtures that gave the mating reaction and conjugation consisted of any one of the caryonides 2b1, 2b2, 3a2, 4b1 or 4b2 mixed with any one of the caryonides 1b2, 2a1, 2a2, 3a1, 5b1 or 5b2. Those that failed to react or conjugate consisted of mixtures of two of the former group of caryonides or of two of the latter group. The two groups of caryonides are thus of two different mating types: mating reactions and conjugation occur when caryonides of these two types are mixed, not when two of the same type are mixed. Thus, in this sample of stock F, only two mating types appeared. In other experiments, many

TABLE 3

RESULTS OF MIXING DIFFERENT EXCONJUGANT CARYONIDES OF STOCK F, GROUP 1, *Paramecium aurelia*

In the square formed by the junction of each row and column is a symbol indicating whether the mating reaction and conjugation occurred in the mixture of the two caryonides shown on that row and column + signifies that they did occur, – that they did not

CARYONIDES

CARYONIDES	2b1	2b2	3a2	4b1	4b2	1b2	2a1	2a2	3a1	5b1	5b2
2b1	–	–	–	–	–	+	+	+	+	+	+
2b2	–	–	–	–	–	+	+	+	+	+	+
3a2	–	–	–	–	–	+	+	+	+	+	+
4b1	–	–	–	–	–	+	+	+	+	+	+
4b2	–	–	–	–	–	+	+	+	+	+	+
1b2	+	+	+	+	+	–	–	–	–	–	–
2a1	+	+	+	+	+	–	–	–	–	–	–
2a2	+	+	+	+	+	–	–	–	–	–	–
3a1	+	+	+	+	+	–	–	–	–	–	–
5b1	+	+	+	+	+	–	–	–	–	–	–
5b2	+	+	+	+	+	–	–	–	–	–	–

STOCK F

other exendomictic and exconjugant caryonides were examined and all were found to react and conjugate when mixed with one or the other [1] of the two mating types indicated in Table 3 No additional or different types appeared and non-reactive caryonides were not found. Stock F thus consists of two mating types and every individual is of one type or the other In like manner, the stocks J, R and S of group 1 were shown to consist of two mating types each.

Stock K will be used as an example of the second group of stocks—those that react at low temperatures and during the night. The stocks A, C, D, E, G, H, and L also belong to this group and show the same phenomena as those now to be set forth for stock K In most of the work with this group, the mating reaction itself was not observed because of the inconvenient hours at which it usually occurs Instead, as mentioned above, mixtures were made, put at 17° to 19° C over night, and observed for conjugation the following morning Table 4 gives the results with 16 exconjugant caryonides of stock K, using the same symbols as in Table 3 No conjugation occurred in any mixtures of two cultures of the same

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[1] In this stock, and in other stocks of all three groups, caryonides exist which react and conjugate with both mating types of their stock Unlike the superficially similar situation in P. bursaria (Jennings, 1938a), however, mating also occurs readily between individuals of the same caryonide Such caryonides thus appear to contain not a third type, but both of the two types characteristic of their stock This matter will be dealt with fully in later papers from this laboratory

TABLE 4

Results of Mixing Different Exconjugant Caryonides of Stock K, Group 2, *Paramecium aurelia*

In the square formed by the junction of each row and column is a symbol indicating whether conjugation occurred in the mixture of the two caryonides shown on that row and column + signifies that it did occur, − that it did not

CARYONIDES

CARYONIDES	31a	33a	34a	35a	37b	38b	39b	41b	44b	45b	33b	34b	37a	41a	44a	45a
31a	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
33a	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
34a	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
35a	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
37b	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
38b	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
39b	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
41b	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
44b	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
45b	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
33b	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
34b	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
37a	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
41a	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
44a	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
45a	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−

STOCK K

caryonide, but among the 120 possible different mixtures of two caryonides, conjugation took place in 60, not in the other 60. The mixtures that conjugated consisted of any one of the caryonides 31a, 33a, 34a, 35a, 37b, 38b, 39b, 41b, 44b, or 45b mixed with any one of the caryonides 33b, 34b, 37a, 41a, 44a, or 45a. Those that failed to conjugate were mixtures of two caryonides of the former group or two of the latter. The caryonides of one group are thus of one mating type and those of the other group are of another mating type, and conjugation occurs only when the two types are mixed. In stock K, as in stock F, only two mating types appeared, for all of the hundreds of exendomictic and exconjugant caryonides examined in other experiments conjugated when mixed with one or the other of the two types shown in Table 4.

Similar results were obtained with the third group of stocks (M, Q, and Y) which react between 1 A.M and 1 P M. Stock Q will be used as an example of this group, identical results were obtained with the other two stocks M and Y. Table 5 gives the results of an analysis of 17 exconjugant caryonides of stock Q. No conjugation occurred in any mixtures of two cultures of the same caryonide, but the 136 possible different mixtures of two caryonides showed that two mating types were present eight caryonides were of one type and nine of the other. The 72 different mixtures consisting of two caryonides of different type all conjugated, the 64 different mixtures consisting of two caryonides of the same type did not. In further studies on hundreds of other exconjugant and exendomictic caryonides of stock Q, the same two types constantly reappeared and no new ones. all conjugated when mixed with one or the other of the two types shown in Table 5.

Thus, each of these 15 stocks, belonging to three diverse groups, consists of two mating types. The remaining two stocks, B and W, are different. In each of them, hundreds of exendomictic caryonides were mixed together under conditions favorable for conjugation, but not one pair of conjugants ever appeared. Are these "non-conjugating" stocks? Or do they require for conjugation conditions different from those re-

TABLE 5

RESULTS OF MIXING DIFFERENT EXCONJUGANT CARYONIDES OF STOCK Q, GROUP 3, *Paramecium aurelia*

In the square formed by the junction of each row and column is a symbol indicating whether the mating reaction and conjugation occurred in the mixture of the two caryonides shown on that row and column + signifies that they did occur, − that they did not

CARYONIDES

CARYONIDES	2b1	3b1	4b1	5b1	7b2	13b1	16a2	30a2	1b2	2b2	3b2	4b2	5b2	7b1	13a2	19b1	21b2
2b1	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
3b1	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
4b1	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
5b1	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
7b2	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
13b1	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
16a2	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
30a2	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
1b2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
2b2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
3b2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
4b2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
5b2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
7b1	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
13a2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
19b1	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
21b2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−

STOCK Q

quired by the three groups of stocks already described? Or does each of these stocks consist of but one mating type?

The problem was easily solved by mixing caryonides of stocks B and W with caryonides of other stocks. Stock B gave the mating reaction and conjugated when mixed with type II from stocks R or S, but not when mixed with type I. Stock W invariably conjugated when mixed with one of the two mating types of stock K, but not when mixed with the other Thus, stocks B and W are not "non-conjugating" stocks and do not require conditions for conjugation other than those already set forth, moreover, each does contain at least one mating type.

In order to discover whether in each of these stocks all the caryonides were of the same mating type, each caryonide derived from a group of exendomictic individuals was separately tested Of 75 exendomictic caryonides of stock B, 28 were non-viable and the remaining 47 all reacted with type II of stock R. All the viable caryonides were therefore of type I Of a group of 81 exendomictic caryonides of stock W, 76 were viable and all reacted with one of the two types in stock K, none with the other type It thus appears that in each of the stocks B and W all of the viable caryonides are of one mating type

It is of interest that one of these stocks, W, is the famous long-lived stock cultivated since 1907 by Woodruff (1932) Woodruff (1921) has twice obtained conjugation in it. This suggests that it sometimes gives rise to the other mating type found in stock K, but this has not yet happened during my four years of observations on it.

After these unusual results were obtained with stocks B and W, new collections were made from the stream in Woodstock, Md., from which stock B had been obtained Four individuals obtained from one quiet pocket of the stream gave rise to the four stocks N, O, P, and T In each stock, endomixis was induced and the exendomictic caryonides tested In every case, they failed to react with each other or with type I, but did react and conjugate with type II from stocks R or S. They were thus all like stock B, consisting exclusively of type I However, not all stocks from this stream are like this, for three other individuals collected from another pocket of the stream gave rise to the stocks U, V, and X which belonged to group 2 and contained two types each.

The general result of this survey of 24 stocks of *P aurelia* is thus to show that all consist of mating types, most of them of two types that react and conjugate with each other, but some of them apparently consisting mainly or exclusively of only one type If these 24 stocks, collected from North Carolina to Massachusetts, are a fair sample of the species, it can be concluded that "non-conjugating" or even "rarely conjugating" stocks do not exist all conjugate regularly when the appropriate mating types are mixed together under appropriate conditions Mating types thus appear to be of universal occurrence in *P aurelia*. Previous failures to observe them must be ascribed not to their absence, but to failure to grow the types separately and to mix them together in proper combinations under the necessary conditions

III THE NUMBER OF DIVERSE MATING TYPES IN P AURELIA AND THEIR INTERRELATIONS

The questions now arise as to whether the mating types in different stocks are alike or not, how many diverse types exist, and how they are interrelated In order to answer these questions, all possible combinations of two were made among the stocks B and W and the two types from each of the other 15 original stocks These 496 different mixtures were made with the results shown in Table 6 In 395 of the mixtures conjugation did not occur, in the remaining 101, it did The mixtures in which conjugation occurred are classifiable into three groups in the following way

The first group involves the stocks B, F, J, R, and S The two types in stocks R and S are the mating types I and II, as set forth in my earlier papers (Sonneborn, 1937, 1938) Stock B consists of type I only, as shown in the preceding section Of the two types found in each of the stocks F and J, one is type I, for it conjugates with type II and not with type I from the other stocks, and the other is type II, for it conjugates with type I but not with type II from the other stocks Among these five stocks, conjugation occurred when type I from any of the five was mixed, in any of the 20 possible different combinations, with type II from any of the four stocks in which it occurs. The remaining 16 different combinations among these stocks involved mixtures of two cultures of the same type and no conjugation occurred. Moreover, no conjugation occurred in any of the 207 possible mixtures of either type I or type II from these stocks with any of the types found in the remaining 12 stocks. Hence, neither type I nor type II occurs in those stocks.

The second group of mixtures yielding conjugation involved the nine stocks A, C, D, E, G, H, K, L, and W. As types I and II do not occur in these stocks, the two types in any one of them, stock A for example, require new designations. They will be called mating types III and IV That the other stocks of this group contain the same types is shown in Table 6 by the results of mixing them with types III and IV of stock A Thus stock W conjugates in mixtures with type III from stock A, but not with type IV; therefore, the one type existing in this stock must be type IV In each of the other seven stocks of this group, one type conjugates in mixtures with type III from stock A, but not with type IV, the other conjugates in mixtures with type IV from stock A, but not with type III. The former is thus type IV, the latter type III In agreement with this, each of the possible 72 different combinations between types III and IV from different stocks yielded conjugants, whereas none were found in any of the 64 possible combinations between two cultures of type III or two of type IV. Types III and IV in these nine stocks not only failed to conjugate in mixtures with types I and II, but also in all of the 102 possible mixtures with the two types in the remaining three stocks. The latter, therefore, do not contain types I, II, III, or IV

The third group of mixtures yielding conjugation involved combinations among the types in these three remaining stocks. As the four types previously discussed do not occur in them, the two found in any one stock—M, for example—will be designated mating types V and VI. As Table 6 shows, the two types in stocks Q and Y must also be types V and VI; for one conjugates with type VI, but not V; and the other conjugates with V, but not with VI from stock M. In agreement with this, conjugation occurred in each of the six possible

TABLE 6

RESULTS OF MIXING IN ALL POSSIBLE COMBINATIONS OF TWO THE 32 MATING TYPES FOUND IN 17 DIFFERENT STOCKS OF *Paramecium aurelia*

In the square formed by the junction of each row and column is a symbol indicating whether conjugation occurred in the mixture of the two types shown on that row and column + signifies that it did occur, – that it did not The capital letters give the names of the stocks, the Roman numerals designate the mating types

			Group 1									Group 2																	Group 3					
			I	I	I	I	I	II	II	II	II	III	III	III	III	III	III	III	III	IV	IV	IV	IV	IV	IV	IV	IV	IV	V	V	V	VI	VI	VI
			B	F	J	R	S	F	J	R	S	A	C	D	E	G	H	K	L	A	C	D	E	G	H	K	L	W	M	Q	Y	M	Q	Y
Group 1	B	I	–	–	–	–	–	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	F	I	–	–	–	–	–	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	J	I	–	–	–	–	–	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	R	I	–	–	–	–	–	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	S	I	–	–	–	–	–	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	F	II	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	J	II	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	R	II	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	S	II	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Group 2	A	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	C	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	D	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	E	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	G	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	H	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	K	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	L	III	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–
	A	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	C	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	D	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	E	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	G	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	H	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	K	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	L	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	W	IV	–	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Group 3	M	V	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+
	Q	V	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+
	Y	V	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+
	M	VI	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	–	–	–
	Q	VI	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	–	–	–
	Y	VI	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	–	–	–

combinations of type V with type VI from different stocks, but not in any of the six possible combinations of two type V cultures or two type VI cultures from different stocks.

The types in the remaining nine stocks were not tested with all the other stocks, as Table 6 shows this is unnecessary. All that is required to ascertain the types in a new stock is to test them against one standard culture of each of the six diverse mating types, for the behavior of any type is consistent· if it reacts with one type from any one stock, it will react with this type from any other stock, and if it fails to react with one type, it will not react with this type from any stock. Using this method of identification, it was found that the stocks N, O, P, and T were of type I, because they reacted and conjugated with type II, but not with any other type. In like manner, the two types found in stock Z were found to be types I and II And those in the stocks I, U, V, and X were types III and IV, for one type from each of these stocks reacted and conjugated with type IV, but not with any other type, and the other reacted and conjugated with type III, but not with any other

The 26 stocks are thus divisible into three groups on the basis of the mating types they contain. In the first group are stocks containing mating types I or I and II, these are the ten stocks B, F, J, N, O, P, R, S, T, and Z Stocks of the second group contain mating types IV or III and IV, they are the 13 stocks A, C, D, E, G, H, I, K, L, U, V, W, and X In the third group are stocks containing mating types V and VI, these are the three stocks M, Q, and Y This grouping of the stocks on the basis of the mating types they contain gives the same results as grouping them on the basis of the environmental conditions required to get the types to react and conjugate. Types I and II, constituting group 1, react at any hour of the day or night over the entire range of temperatures tested (9° to 32° C.). Types III and IV, constituting group 2, react at night below 25° C. Types V and VI, constituting group 3, react below 28° between 1 A.M and 1 P M Thus, the three groups of stocks differ not only in the mating types they contain, but also in the conditions required for conjugation

The failure to obtain conjugation between stocks of different groups is not, however, due to the differences in external conditions required for conjugation. Types I and II react under conditions favorable for any of the other types; and the types of groups 2 and 3 all react between 1 A M and 9 A M. at low temperatures The mixtures between stocks of different groups were always made under conditions favorable for both groups involved Their failure to yield conjugants must thus have been due to internal, not external, blocks to union.

From the observations set forth up to this point, the mating system in *P. aurelia* can be formulated in four propositions 1.—The species consists of three groups of stocks differing in mating types and in the conditions required for conjugation 2.—Each group includes only two mating types 3—Each stock consists of one or both of the mating types characteristic of its group 4—Conjugation occurs only between the two mating types of the same group, so that the three groups do not interbreed These mating relations of the different types and groups are summarized in Table 7 They show on a larger scale a difference between *P. aurelia* and *P. bursaria* that appeared when only one stock of *P. aurelia* had been examined For, in *P. bursaria*, the mating types occur in groups of four

TABLE 7

RESULTS OF MIXING THE SIX MATING TYPES OF *Paramecium aurelia*

+ signifies that conjugation occurs in the mixture of the two types on the corresponding row and column, – that it does not The six types fall into three groups of two types each, with conjugation only between the two types of the same group

			Group					
			1		2		3	
		Type	I	II	III	IV	V	VI
Group	1	I	–	+	–	–	–	–
		II	+	–	–	–	–	–
	2	III	–	–	–	+	–	–
		IV	–	–	+	–	–	–
	3	V	–	–	–	–	–	+
		VI	–	–	–	–	+	–

or more with conjugation taking place between any two of the four or more types of a group (Jennings, 1938a and b); whereas, in *P. aurelia*, there are invariably two mating types to a group and conjugation occurs between them only.

The sharp division of the species *P. aurelia* into three groups of non-interbreeding stocks raises the question of whether these different groups are different species. All these groups conform to the specific description of *P. aurelia*, possessing two vesicular micronuclei Within each group of stocks there are, under certain conditions, slight differences in body size and form; but consistent morphological characters differentiating all the stocks of one group from all of those of another, have not been found. The three groups do differ consistently in the mating types they contain and in the conditions required for conjugation. On the basis of the latter, the group to which a new stock belongs could be determined without testing against the six standard types If conjugation occurred readily above 27° C. and equally well at all hours of the day and night, the stock belongs to group 1; if it occurred only below 25° and only at night or early morning, the stock belongs to group 2; if it occurred only below 27°, and only between 1 A.M. and 1 P.M., the stock belongs to group 3. As the different groups of stocks do not interbreed, they would be considered by some (Dobzhansky, 1937) to be separate species. Practically, however, it would require observations of such a special kind to ascertain the species that it seems inexpedient for the present at least to set up these three groups of stocks as separate species

The mating reaction and conjugation have thus far been dealt with as if they were invariably correlated. This is, in fact, the usual condition. conjugation ordinarily follows the mating reaction. In at least one combination of mating types, however, a weak but definite clumping reaction regularly occurs under appropriate conditions and is never followed by conjugation. This reaction appears between 1 A.M. and 1 P.M. at temperatures below 27° C. in mixtures of type II with type V; but only when the two cultures mixed are in the most favorable condition for conjugating, that is, when each gives immediate strong reactions in mixtures with the other type of its own group. The same result is obtained regardless of which stocks are used as sources for the two types type II from any of the five stocks F, J, R, S, or Z in which it exists reacts with type V from any of the three stocks M, Q, or Y in which it exists In all these mixtures there are formed pairs or small clusters that go through the characteristic early stages of the mating reaction and then break apart with a sharp jerk That the reaction involves animals of both types is evident when mixtures are made between small type II and larger type V animals, or vice versa the unions are invariably between animals of diverse sizes In mixtures of about 50 animals of each type, usually only one or two pairs or small clusters are present at any one time and these remain together for only a minute or less There are frequently intervals of one or a few minutes in which no pairs are present, but new pairs form repeatedly throughout the ordinary period of reactivity of group 3 After this period the reaction ceases; but if the mixture is kept until the following day, the reaction is repeated during the forenoon. During the period of reactivity, the behavior is such as takes place near the end of the daily reactive period in mixtures of type V and type VI, when temporary pairs or clusters form for a short time and break apart without conjugating

This type of reaction has not been found in any other combination of mating types belonging to different groups If it existed, one would expect to observe it most favorably between 1 A M. and 5 A M in the case of mixtures between groups 1 and 2, and between 4 A M. and 5 A.M. in the case of mixtures between groups 2 and 3. In the several trials made at these hours, the results were completely negative. The occurrence of clumping without conjugation in certain mixtures of types belonging to different groups and not in others appears to resemble the results of Strehlow (1929) on the alga Chlorogonium. When + and − gametes of the two species *C. euchlorum* and *C. elongatum* were mixed, in certain interspecific combinations, the gametes adhered to each other, in other combinations not, and in no case were zygotes formed. The regular occurrence of the clumping reaction between types II and V, which do not interbreed, suggests that the four types I, II, V, and VI include two modifications of one original type and two of another For types I and V are similar in that both react with type II, and types II and VI are similar in that both react with type V In agreement with this, other similarities between types I and V, on the one hand, and between types II and VI, on the other, have been found These similarities suggest common origins, namely, that two, and possibly all three, of the pairs of mating types may be diverse modifications of a single original pair of types Full discussion of this question will be given in a later communication, after other pertinent evidence has been presented.

Do the three pairs of mating types reported above include all the types existing in *P. aurelia?* As only 26 stocks have been examined, and as all but one of these (the one from California) come from the eastern United States between North Carolina and Massachusetts, it is possible that further search, particularly in other localities, will turn up more pairs of types. I should be glad to receive and analyze cultures collected elsewhere

IV THE RELATION OF MATING TYPES OF PARAMECIUM TO SEXUALITY

The recent work on mating types in *Paramecium* has demonstrated among the conjugants the existence of physiological diversities that are strikingly similar to the sexual differences between gametes in some of the unicellular green algæ (Strehlow, 1929, Moewus 1933, 1935). In the latter, cells capable of uniting in copulation are of two types, plus and minus, when cultures of these two types are brought together under appropriate conditions, they at once form clumps ("Gruppenbildung") and proceed to copulate. The plus and minus gametes are morphologically and functionally alike, but, as copulation takes place only between cells of different types, they are physiologically diverse. In these respects, therefore, the plus and minus sexes in the unicellular algæ are like the mating types of *Paramecium*

There are, however, certain differences between the phenomena in the two groups of organisms In the algæ, the two sexes have been shown (Moewus, 1933) to elaborate specific "sex stuffs" which can be obtained from the fluid they have lived in Attempts to demonstrate such "stuffs" in *Paramecium* have not been successful A further difference exists in the number of kinds of mating classes In the algæ, there are always only two kinds, though each kind may exist in varying strengths, in *P aurelia* there are likewise but two kinds in any mating system, but in *P bursaria* (Jennings, 1938a and b), there may be four or five different mating types in one system Finally, in *Paramecium* all the mating types are functionally hermaphroditic, each conjugant of a pair fertilizing the other one, while in the unicellular algæ reciprocal fertilization does not occur

In view of these differences, it has been held that the similarities between the phenomena in the unicellular algæ and in *Paramecium* are not indicative of fundamentally similar processes, indeed, that in the former they are to be considered sexual phenomena, in the latter, not. The chief fact held to show that the phenomena of mating types in *Paramecium* are not sexual is the hermaphroditic condition of all the types As each conjugant produces both a "male" and "female" pronucleus, the conjugant as a whole cannot be male or female On the other hand, there is evidence in other ciliates that vestiges of the hermaphroditic condition can coexist with individual sex differences. In the Vorticellidæ, the conjugants are markedly dimorphic as well as functionally diverse· the microconjugant is motile and fertilizes the sessile macroconjugant Yet, in both conjugants two pronuclei are formed as in the ciliates with morphologically identical conjugants and reciprocal fertilization. Moreover, in one of the Vorticellidæ, *Zoöthamnium arbuscula*, Furssenko (1929) gives some evidence that even reciprocal fertilization may occur, though followed by disintegration of the syncaryon in the microconjugant. It seems, therefore, that hermaphroditism need not be completely incompatible with other aspects of sexual diversity. With respect to that aspect of sex concerned with fertilization itself, the two cells that come together may be hermaphroditic, while with respect to that aspect of sex concerned with bringing together the cells, they may be diverse. That is the situation in *Paramecium*. However, opinions may differ as to whether processes concerned simply with bringing cells together for mating are in themselves sexual. It appears desirable, in the present state of knowledge, to focus attention on the facts rather than on their interpretation Therefore, the interpretive terms "sexes," "sex types," and "sex reaction types" used in previous papers have been replaced in this paper by the purely descriptive term "mating types."

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THE TRANS NEPTUNIAN PLANET SEARCH*

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(*Read, April 21, 1938*)

The ninth planet, Pluto, was found early in 1930, terminating the long search for Lowell's mathematically predicted Planet X Final success, after years spent in searching with inferior instrumental means, came in scarcely a year after the completion of the specially designed search telescope—indeed the tenth search plate made with this powerful instrument recorded the planet although it was not until the examinations of plates of the following season that Mr Tombaugh actually found the planet. Then quite naturally there appeared to us weighty reasons why the Lowell Observatory should proceed with the larger campaign of searching a wide ecliptic belt of the heavens for still more distant members of the solar system There were reasons for expecting such bodies might exist For example Pluto with his smallness compared with his neighbors, Neptune and Uranus, suggested striking similarity now of the Solar planet system to that of the Jovian satellite system in that both systems possess, we see, smaller order of bodies in their outer portions and there is then the intimation that we may expect to find other more distant planets of Pluto's order of size

Furthermore we believed the search could be well done because of very favorable surrounding circumstances good skies, very efficient instrumental means, perfected methods, and an enthused observer of high technical skill and experience Yet we from experience realized the task was not an easy one because it involved searching a wide area of the heavens and the careful testing of many millions of stars for planetary motion, but the search needed to be made.

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Perhaps a little ought here to be said of the manner of such searching Fortunately the observer rides the swiftly moving Earth which by its orbital motion carries him past any distant planet causing it to appear to shift from night to night seen against the far background of fixed stars The procedure is then to photograph the identical region of sky, using the same guide star, on two different plates two or a few nights apart, for then the distant planet will be a little shifted on the two plates Thus the observer continues to make such matched pairs of plates of the sky until all of it is covered which is to be surveyed. The observer makes these pairs of duplicate plates as perfect as it is possible to make them, and especially must he keep them free of dust. This is most important for it takes ten times as long to examine the plates as it does to make them, and the tiny speck of dust that looks like a star image can cost much time and trouble in searching the plates

The two members of these pairs of duplicate plates are then placed under the two microscopes of that most efficient Blink comparison machine, and the observer proceeds to examine them until every pair of the many thousands of star images on the plates have been carefully tested for motion, because it is only by shift motion that we could recognize such a distant planet Since furthermore we can expect, in the whole sky, only one (or possibly two) such planets the observer must be over alert lest he pass over the coveted little planetary images. He must not make even one miss Such examination must be far more precise and painstaking than if he were looking for proper motion stars, variable stars or the like. He, as a matter of fact, sees the numerous variable stars, asteroids and nebulæ, etc., which in passing he marks and lists as by-products of the survey.

Since 1930, except for some time at the University, Mr Tombaugh has given all his time to this search. He has pushed it forward with praiseworthy care, energy, and skill. Most of the time during the last 3 or 4 years he has been able to devote all his energy to the critical examination

…ed by one 14 X 17 inch plate

of the plates, for a technical assistant has been since then available to make the exposures of the plates at the telescope. This has shortened the time and lessened therefore the overlap of plates, which much reduces the total work

Thus far Mr. Tombaugh has carefully examined every star for planetary motion in 27,000 square degrees, or sixty-five per cent of the whole sky The illustration in Fig 1 shows a map of the whole sky, of which the shaded part denotes the portions of the heavens that have been examined to April 1 The heavy curved line is the ecliptic, which is the most likely portion of the sky for planets, although the high inclination of Pluto's orbit and of those of some of the outer satellites of Jupiter and Saturn suggested it would be wise to extend the search also to considerable distances north and south of the ecliptic Below, midway in this figure is a small white rectangle which denotes the size of one of the 14 × 17 inch search plates on the scale of this map of the heavens, and on this white rectangle is a tiny black spot of just the size to include five square degrees of sky Within this small area of a plate in the Milky Way east of Sirus were counted 15,000 stars on one of the original plates While on the average the stars are not nearly as numerous as they are in the Galaxy still the number of stars thus far examined for planetary motion amounts to about 35,000,000 The total area covered is 8,000 times that represented by this tiny spot, counting the needed over-lap of the plates, and the examination of the duplicate plates, the survey has included about 70,000,000 star images to date

In the course of the work a number of suspected planetary images were met, and a few of these seemed very promising, but in running them down all these proved to be false leads of spurious tiny specks that perfectly simulated real planetary images Some of these involved the securing of additional check plates in order to decide that they were not true images, for nothing could be taken for granted with such cases.

The result then is that no outer planet has yet been found by this search beyond Pluto. Still it is well that we have this knowledge of the solar system, even though the result in that sense happens to be negative. There appears to be no outer planet as bright as the sixteenth photographic magnitude for the reach of the survey is to the 16th stellar magnitude a little less in the lowest southern declinations and a little more in the higher declinations. The search has been thorough and homogeneous with standardized plates and methods. It is hoped in a few months to complete the few unfinished areas when the sky will be covered from near 50 degrees S. to 60 degrees N. declination for most of the northern sky.

Mention has been made of byproducts of the search, and a few comments and slides touching these matters may be of interest. The asteroids, those little bodies belonging mainly between the orbits of Mars and Jupiter, move rapidly and so leave their trails on these plates. More than 3,000 asteroids have been recorded on the plates and their trails

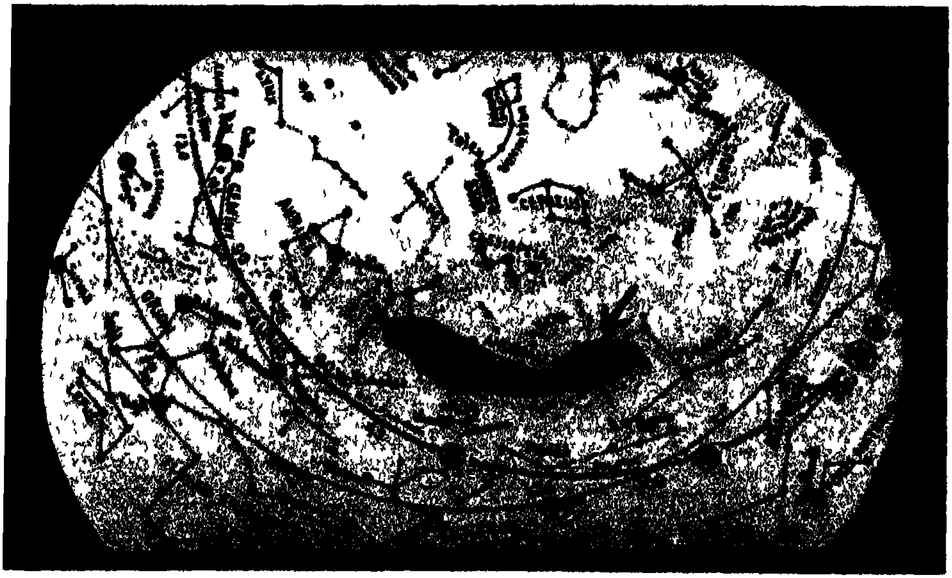

Fig. 2. The arrow points to the shaded portion, which indicates the position and extent of the *"Great Perseus-Andromeda Stratum of Nebulæ,"* discovered in the planet search.

marked The asteroids have of course been observed to become rare in those parts of the sky at considerable distances from the ecliptic The positions of the asteroid images on these plates are being measured and published because such information is much desired by those investigating this remarkable and multitudinous group of bodies While the majority of these images are the record of known objects there will be found among them many new asteroids and some known ones for which more data are much to be desired.

It is estimated that more than 30,000 nebulæ are recorded by these search plates and a full record has been kept of them, and some study has been made of their distribution over the sky, counts having been made of their numbers in selected areas of the heavens In the autumn of 1936 Mr. Tombaugh came upon a remarkable rich cloud of nebulæ, which is illustrated in the shaded region of Fig 2 of the sky map This grouping of nebulæ is in Perseus and Andromeda, covers about 300 square degrees, and includes 1,800 individual objects. All are small and rather faint, indicating they are distant and a remarkable aggregation of island universes.

Of course numerous variable stars are also recorded. These naturally are of short period, *i e.* those that change appreciably in two or three days Some of these are of exceptional interest and new They are marked on the plates and also listed in the search records.

This extensive and uniform library of sky photographs will have other values than those indicated here and should be fruitful in later years in other studies

In conclusion, it need hardly be stated in the face of such evidence as has been given that Mr Tombaugh merits high praise for the keen interest, skill, and untiring energy with which he has carried forward this search. Also for making many excellent search plates credit is due Messrs. Frank K. Edmondson and Henry L. Giclas. And finally thanks are due to the American Philosophical Society for its aid of two grants from its Penrose Fund.

THE PLANETS FROM OBSERVATIONS AT THE LOWELL OBSERVATORY

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(Communicated by V. M. Slipher)

(*Read April 21, 1938*)

Abstract

This observatory has emphasized the study of the planets since 1894, and the present paper briefly discusses the observations of Mercury, Venus, Mars, Jupiter, and Saturn, and their atmospheres. Direct photographs portray the general appearance of these planets, significant changes, as well as examples of tell-tale phenomena observed during the past thirty years.

Mercury appears as atmosphereless and unchangeable as our moon and, keeping always the same face to the sun, thus is completely desolated by a surface temperature of 280° to 400° C.

Venus' true surface is hidden by a considerable atmosphere, rendered virtually opaque by some medium, probably dust, and hence her day is not yet definitely determined but is long. Her atmosphere contains 400 to 500 meter atmospheres of CO_2, but oxygen and water have not yet been detected. The temperature of her actual surface is more difficult to determine than Mercury's, but appears about 50° C.

Mars is analogous to the Earth, and its surface is marked by polar snow-caps and blue-green areas which change with its seasons, has a moderate surface temperature, and displays an atmosphere of considerable extent which supports clouds at relatively great heights and scatters light to an amazing degree, but is very changeable in the latter respect.

Jupiter presents a belted surface of mobile, changeable, and vari-colored clouds of unknown composition, but not of water-vapor. The surface temperature is low—near $-120°$ C., but the great activity of his surface indicates a fairly hot interior. His overlying atmosphere, containing CH_4 and NH_3, is very transparent although of a molecular population comparable with the Earth's.

Saturn closely resembles Jupiter, but its surface displays less activity and less conspicuous markings except in rare instances such as the great white spots of 1875 and 1933. The surface temperature is near $-150°$ C., and the composition and behavior of its upper atmosphere simulates Jupiter's.

The special aim of the Lowell Observatory since its founding has been the study of the planets of our solar system, beginning with their present state and looking thence to their evolutionary history. To accomplish this purpose it has been necessary to collect information, as accurate and

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extensive as possible, by well tested means and methods, and to plan the program in ways to secure data which bear upon the various phases of the problem. To this end the program at Flagstaff has included in addition to visual and photographic studies long continued spectrum studies and more recently radiometric observations.

It is intended here to consider chiefly results obtained from the visual and photographic observations of the surfaces and atmospheres of Mercury, Venus, Mars, Jupiter, and Saturn.

Diverse as the planets are today, they are all representative of certain evolutional processes and so knowledge of one member may throw light upon the development of others Therefore, as intimate knowledge as possible of the several planets is important Thus they have been closely studied visually at this Observatory for more than forty years, and during the last third of a century the visual observations have been supplemented by direct photographs The photographic record has been kept as homogeneous and as complete as possible so as to afford a permanent record with which future results may be compared. Early experience has shown that photographs of the planets in light of different colors were valuable aids in their study Thus for more than fifteen years we have kept a fairly complete record of the several planets in blue light, simultaneous with the usual series in yellow light And for some years these series have been supplemented and extended by photographic studies in ultra-violet and infra-red light. Indeed, advantage has always been made of any new means or methods that afforded any new approaches to these planetary investigations

The camera system as employed on the 24-inch refractor magnifies the planet about 200 times on the original negatives. The exposure times vary with the planet, plate, and filter, but generally range from 1 to 60 seconds.

A very large number of photographs totaling about 500,000 images of the planets has been secured during the past thirty-five years Comparison of photographs taken at different times bring out many interesting and instructive features and phenomena that might otherwise be missed or less well recorded.

It will be understood that because of the graininess of plates not much of the delicate detail of the original photographs can be reproduced with a projecting lantern This is unfortunate because in the fine detail of the plates is often the most instructive part of their record.

MERCURY

The markings on Mercury are faint, diffuse, and irregular in form and arrangement. They are of a straw-colored grey, and bear the look of soil or rock These facts and his low albedo imply that we see simply barren rock or sand weathered by eons of exposure to the hot Sun There is no distinctive color in any part of the planet He has no polar caps, and the fixity of the markings affords evidence that the planet's rotation period is the same as its period of revolution. The visual and photographic observations reveal no evidence of any clouds, *i e.* of any sensible atmosphere His surface presents as dead an appearance as does that of our own Moon With no air to mitigate the intense heat of the sun which is seven times as intense as the Earth receives, its surface temperature, as measured with the thermocouple is high—at aphelion 280° and over 400° C. at perihelion—a temperature sufficient to melt such metals as lead and zinc Such intense heat would have speedily dissipated his original atmospheric envelope Thus, one imagines the desolation of his surface is complete.

VENUS

Venus, being relatively near us, displays a correspondingly large disk, but one which has proved singularly baffling. An air-enshrouded planet we know her to be, by her high albedo, by the observed prolongation of the horns of her crescent beyond the geometric half circle, and by the variable atmospheric spots on her ultra-violet photographs. It is this very atmosphere that prevents us seeing her actual surface clearly (Pl. I). Thus she is difficult of observation. The length of her day is not satisfactorily determined. Still from spectrographic and other evidence her diurnal turning—her rotation period—is doubtless very slow but whether her day and year are exactly equal there remains some doubt. It is hoped to gain further knowledge of her period of rotation from the markings on the ultra-violet photographs. But these as yet have proved too ephemeral to indicate rotation (Pl II).

Spectrographic investigations at Flagstaff and elsewhere of Venus have failed to reveal water vapor or oxygen in her atmosphere, but Dunham at Mt. Wilson discovered carbon dioxide to be present, and the quantity has been determined by Adel at Flagstaff as quite large, nearly 500 meters at atmospheric pressure. However, something more and different is required to account for the high reflectivity of her atmosphere which gives her a high albedo and prevents us from seeing her surface. It now seems more probable than ever that this something is dust, as suggested long since by Lowell. A dust laden atmosphere would appear to account satisfactorily for all the observed facts.

Venus, situated about seven-tenths our own distance from the sun, gets about double our supply of solar radiation and her surface temperature is relatively higher than the Earth's. The temperature of her true surface cannot be so definitely stated as in the case of Mercury, but an effective temperature near freezing for the integrated radiation measured radiometrically is indicated for her radiating layer. Analysis of band spectra by Adel indicates a surface temperature higher than 50° C.

MARS

It is a fortunate circumstance that the planet Mars, the one most favorably situated for observational study should duplicate so closely our Earth in seasonal effects, intake of solar radiation, and in other respects as will appear in what is to follow.

In case of Mars we see a solid surface and deal with a geography and meteorology as real as our own. Quite unlike the markings upon Jupiter and Saturn, where all we see is cloud, in the definite markings on Mars we gaze upon the actual surface features of his globe. His disk we see capped by cloud and snow at the poles, in season, with the intervening area divided between ochre colored desert, and dark blue-green regions which seasonally behave as vegetation Both the polar caps and the blue-green areas are observed to wax and wane in precise step with his seasons. Then there are other changes in some dark markings which do not obey the seasons, but are of a secular nature We find him encompassed by an atmosphere of considerable extent bearing clouds and haze some of which are yellowish and others bluish white in tint Besides, his atmosphere manifests a most amazing influence on light, an influence perhaps out of all proportion to the density of it, being usually so opaque to the short waves as to obliterate all the surface markings, whereas this same blue light we have seen to pass readily through the atmospheres of Jupiter and Saturn without noticeable effect. Yet at other times, his air clears up in some strange manner so as to become nearly transparent to this very same light, as we shall now see in the photographs

Plate III shows photographs of Mars displaying seasonal change in his polar snow caps and in the blue green areas from Martian date (upper hemisphere) March 2 to August 21. With the advance of summer his snow cap dwindles and the dark regions increase in intensity. This is the usual seasonal behavior, and in the main repeats itself every Martian year.

Plate IV shows independent drawings of Mars by Trumpler (at left) at Lick Observatory and by the writer at Flagstaff. About 50 canals, oases, and other fine details are common to both observers and they agree substantially as to the position and fineness of the canals and the other features.

Plate V is a group of drawings and photographs displaying the life-history of one of the most remarkable storms ever seen at midday on Mars. Figures 1 and 2 show the normal aspect prior to the storm. The succeeding images display the storm as a bright spot, covering 300,000 square miles on July 9, it changes in its position, size, and form strikingly by July 10, and on the 12th has nearly disappeared. Such striking storms are very rare on Mars, especially in the tropics and at Martian noonday.

Plate VI shows photographs of the same face of Mars taken at different times, displaying remarkable changes in the clarity of his atmosphere. The first image, Fig. 1, is in red light, all the others are in blue light and display various degrees of cloudiness, of general opacity, and of clearness of the Martian atmosphere on different days Photograph Fig 2, taken April 20, 1937, shows much cloudiness. Figure 3 taken a month later, May 20, displays the highest blue transparency of his atmosphere ever observed, the clarity being evidenced by the showing of the dark surface markings. Figure 4 is a blue photograph of the same face of the planet, June 24, 1937, which illustrates how completely the sky of Mars has hazed over again For on June 24 his air had again become opaque to blue light, and no trace of his surface markings shows through These photographs not only prove the existence of a very considerable atmosphere about Mars, but also clearly show that he undergoes meteorological changes not unfamiliar to us here. Figures 5 and 6 are yellow and blue images of another face of Mars taken on May 13, 1937, which display the morning side of the planet covered with a blue-white haze, while the afternoon side was quite clear. Figures 7 and 8 are yellow and blue photographs taken June 1, 1937 Here the blue image shows new large dark areas which are as indicative of the influence of the air of Mars as are their associates, the bright clouds. That these strikingly dark areas on the blue photographs do not belong to the body of the planet is made evident by the yellow photograph, and confirmed by visual observations. It is difficult to say how his atmosphere causes these new "dark clouds", whether they are due to strong local absorptions or to polarization effects or to some other cause it is not now possible to decide.

Other photographs of Mars (not reproduced here) were presented that displayed the southern snow cap at its winter maximum 3,500 miles across in the one case and at the usual summer minimum of 150 miles in another Another set of photographs taken in two different Martian summers displayed the peculiar disintegration of the south snow cap that has repeated itself at the same Martian date since 1845, pecularities which stamp the summer cap as a deposit on the planet's actual surface systematically dissolved with the march of summer there (Pl IV) Still other photographs not only revealed the canals, but it was shown by comparison photographs that they also change greatly in inherent strength from time to time A natural color photograph of Mars was shown which displayed the colors of his surface, portraying the "desert" regions reddish, the dark regions bluish-green, the morning and evening mist bluish-white, and the snow spots nearly pure white

The surface temperature of Mars, the order of which has been indicated by the melting snow caps and other manifestations of his markings, was deduced years ago by Lowell from theoretical considerations as being about 48 degrees F. for the mean More recently it was measured directly with the thermocouple by Coblentz and Lampland, and others, and the result is consonant with the earlier determination. The later measures show that around Martian noonday the temperature of the surface rises to 60 degrees F and higher. This temperature result is not surprising when we consider his low albedo which shows that his surface reflects away only 15 per cent—*i.e.* absorbs 85 per cent of the solar energy reaching it—hence compensating largely for his greater distance from the sun.

Their wide variety and the significant changes his surface features undergo, stamp Mars as a planet the physical state of which is the most Earth-like of any of the planets. When to this we add his matchless canal markings which also undergo significant change, we have the most engaging and at the same time one of the most complex planetary problems of the solar system.

JUPITER AND SATURN

Jupiter and Saturn are observed to be so similar that we may well consider them jointly here. It is clear from these photographs that they differ widely from the terrestrial type of planets, Mercury, Venus, and Mars. The changeable and mobile character of their belted surfaces plainly reveal that they consist of cloud But these clouds we know are not of water vapor as are our own, because their temperatures are too low, being about − 120° C for Jupiter and − 150° C. for Saturn according to the radiometric measures. The composition of their cloud surfaces is not completely known. The spectrographic investigations by Slipher, Dunham and Wildt, and finally the complete identification by Slipher and Adel of all the important absorption bands in the spectra of these planets, have shown the overlying atmospheres contain ammonia gas and much methane. Their bright cloud belts may consist in some degree of crystals of frozen ammonia, but the dark and red belts and other colored darkish markings remain unexplained. The color-filter photographs, give evidence that the gaseous atmospheres of Jupiter and Saturn produce no appreciable scattering and are therefore very transparent, the absorption by the ammonia-methane atmosphere is confirmed by the darkening at the edges of the disk of the Jovian red photographs. The virtual absence of atmospheric scattering denotes that their superficial atmospheres are much less extensive than generally supposed, and suggests a molecular population of the order of the Earth's atmosphere or less. Thus with their cloud surface envelopes near the outskirts of their atmospheres, with the weak solar energy at their great distances, and without water vapor or other effective agent to bar radiation into space, their low cloud surface temperatures seem consonant with the other observations. But this low temperature does not necessarily mean that their centers are cold. In fact the great turbulence of their atmospheric surfaces strongly evidences a considerable temperature gradient beneath. Hence, below their high floating cloud surfaces probably lies an atmospheric ocean which gradually grows denser and warmer downward, before it reaches any solid surface, indeed that these planets possess any solid surface even remotely resembling the Earth's crust is very doubtful

Thus, it has become clearly evident that the surfaces we observe on Jupiter and Saturn are of clouds of some strange composition, being entirely different from the terrestrial type and probably composed of an unfamiliar compound Also it is strongly indicated that the energy that gives rise to these changeable and varigated cloud surfaces comes from within the planets themselves, as there is no observed evidence that they are modified or influenced by diurnal, or seasonal effects of solar radiation

Plate VII are photographs of Saturn, taken from 1909 to 1937, and show various aspects of this beautiful planet and its unique system of rings, and reveal the belts and other features which characterize his surface.

Plate VIII is a drawing and photograph of Saturn showing the great white spot which appeared on his equator in August, 1933. This proved to be the most remarkable cloud disturbance that has been observed on this planet since 1876, when a similar spot was observed by Hall at Washington While we do not know certainly the cause of this phenomenon, we think it might have been due to ammonia vapor which rose from his interior and froze as it reached his high and cold cloud surface.

Plate IX are photographs of Jupiter which exhibit in Figs. 1 and 2 the varied types of features and great complexity of detail that mark his surface in periods of unusual activity. Figures 3 and 4 are two photographs of the same face of Jupiter taken two months and a half apart. They display the widespread changes which may occur there in a short time during periods of great activity. On the upper left side of the disk is the Great Red Spot, a Jovian feature which in its general outline has been fairly stable and persistent for *two hundred and seventy years* This permanency of the so-called Red Spot is in marked contrast to the general changeableness of his other markings.

Plate X displays examples of photographs of Jupiter taken at Flagstaff from 1909 to 1937, which are explained in the notes accompanying the plate.

By piecing together the various bits of evidence we find that the planets differ widely not only in their characteristic surface features but actually in physical conditions. In these respects the major planets stand in a class by themselves and are quite similar But the terrestrial planets, each presents an individual case, and their surface conditions differ very widely. Like statements apply to their comparison as regards their atmospheres based upon spectrum and related observational data

Recapitulating regarding the important matter of their atmospheres, the observations indicate that Mercury possesses no appreciable atmosphere, that Venus has a considerable atmosphere which is largely impenetrable to all wave-lengths of light and therefore its extent and composition is imperfectly known, that Mars has a considerable atmosphere but less than the Earth's and containing scantier amounts of water vapor and oxygen although displaying clouds and familiar meteorological effects, and that his atmosphere is generally transparent to yellow and red light but is peculiarly opaque to light of the violet end of the spectrum, although variable in this respect; and that the superficial atmospheres of Jupiter and Saturn are probably denser than that of any of the above planets and of a different composition containing large amounts of methane and some ammonia, but these are very transparent and manifest themselves chiefly by the greater selective absorption of the red rays.

From these studies it has become evident that, of all the planets, Mars most closely resembles the Earth. The temperature of his surface, the character and behavior of his atmosphere, the presence of clouds, polar caps, and blue-green areas, and all the seasonal manifestations of his surface compose a picture which clearly stamps him as a body the physical state of which does not differ widely from that of our Earth.

In this brief account of the Flagstaff observations of the planets possibly enough has been given to show that they include a wide field for study and that real progress has been made in the study of these companions of the Earth. Yet many questions remain pressing to be answered concerning their surfaces and atmospheres.

EXPLANATION OF PLATE I

Venus

Photographs showing the various phases and true relative sizes of the planet's disk presented during a synodic period

EXPLANATION OF PLATE II

VENUS

Photographs taken in ultra-violet light at different times displaying ephemeral nature of the markings obtained by short-wave light

In this plate are reproduced some representative examples of ultra-violet photographs of Venus such as have been taken at Flagstaff during the past ten years with the hope of gaining further knowledge of her rotation period Photographs of Venus taken in different regions of the spectrum from λ 3500 to λ 12000 have failed as yet to record distinct markings, except those taken in ultra-violet light This series of ultra-violet photographs were taken at different times and display the general appearance and behavior of the markings

FIG 1 An ultra-violet photograph taken February 2, 1937, when the planet was near half phase, which displays the surface strongly marked with bright areas at top and bottom and dark areas in between

FIG 2 This photograph was taken February 17, 1937, and represents about the minimum of markings, being only weakly marked and the disk appears quite uniform

FIGS 3, 4, 5, 6, and 7 Here is a series of such ultraviolet photographs taken on three consecutive days, Fig 3 on June 12, Figs. 4, 5, and 6 on the 13th, and Fig 7 on the 14th, 1935, and therefore should be considered together Those on June 13, were taken at 2 50, 5 50, and 7 15 P M It will be noted that the markings differ on the three days, and even those made at intervals of a few hours on the same day reveal differences in the bright hoods at top and bottom of the disk and in the other markings But the differences disclosed are due to inherent change in the markings themselves and not to rotational shift

Study of many thousands of such photographs made at Flagstaff in the last decade has shown nothing attributable to rotational shift, but on the contrary appears to evidence that the planet turns very slowly

EXPLANATION OF PLATE III

MARS

These are actual photographs of Mars taken through a large telescope showing successive stages in the gradual decrease of the snow at the pole, and the darkening of the planet's tropics with the advance of Martian summer

For the different photographs the Martian seasonal dates, corresponding to our calendar dates for the northern hemisphere of the earth, are.

No 1, March 9 Here the south snow cap is mostly hidden in the antarctic night, but the latitude of the visible edge shows that the snow was approximately 3,300 miles in breadth

No 2, May 11 Here the cap is much reduced in size and the dark areas in the tropics are beginning to strengthen

No 3, May 29 Snow cap is much further reduced in size and the central dark areas have correspondingly increased in intensity

No 4, June 23 The snow cap here is but a few degrees across, and the dark blue-green band is very strong.

No 5, July 31 The polar cap is small, and the tropical band has developed its maximum intensity

No 6, August 21. The polar snow is nearing its normal minimum, being only about 150 miles in diameter The tropical dark band is still intense but a little less so than it was at the end of Martian July

Note that as Martian summer advanced, and the tropics darkened, the polar regions and higher latitude grew a little lighter in tone than they were in Martian spring

This gradual darkening of certain regions of the planet in his summer season and their subsequent fading in winter seems best explained by assuming that these dark areas are due to vegetation

EXPLANATION OF PLATE IV

MARS AND ITS CANALS

Sept 7, 1924	Sept. 10, 1924
Sept 11, 1924	Sept 9, 1924
(Trumpler)	(Slipher)

Drawings of Mars by two observers working independently at two different observatories The drawings at the left are by Dr Trumpler made with the great 36-in refractor of the Lick Observatory, and those at the right are by the author with the 24-in refractor of the Lowell Observatory The observations agree in all essentials and confirm the existence of the canals

The detached spot of snow seen to the left of, and below, the main cap is known as the Mountains of Mitchell, discovered in 1845, and marks a definite milestone in the summer melting of the cap, having been observed there on the same date each Martian summer favorable for its detection since its discovery

PLATE IV

EXPLANATION OF PLATE V

GREAT STORM ON MARS

Photographs displaying the life history of an unparalleled storm over the Martian tropics (bright area near center of disk) on July 9–12, 1922. Area about 400,000 square miles

Both the visual and photographic observations so clearly revealed the atmospheric nature of this bright area as to leave no doubt that it was Martian clouds passing over the surface of the planet The row of images at the left side are drawings from independent visual observations, and at the right are photographs made on corresponding dates as follows

FIG 1 Drawing July 8, displaying the normal aspect of Mars the night before the storm

FIG 2 Photograph June 6, showing nothing unusual present there on that date

FIG 3 Drawing July 9, displaying the storm in the form of a large bright spot which blotted out the true surface of the planet

FIG 4. Photograph July 9, showing the storm area on the night of its first appearance It will be noted that the cloud area is nearly as bright as are the polar caps

FIG 5 Photograph July 9, taken through a blue color-filter with the 42-inch reflector by Dr Lampland This violet light photograph does not show the cloud area any brighter than the rest of the planet's disk, because of the strong yellowish tint of such Martian clouds and because of the Martian atmosphere correspondingly reflected so much blue light as to level out the whole disk of the planet Note how much larger and brighter the polar caps appear in the blue than in the yellow filter photograph

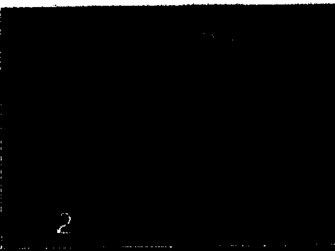
FIG 6 Drawing July 10, displaying marked change in the form of the storm area and revealing that it was drifting downward toward the north pole

FIG 7 Photograph July 10 confirming the change depicted in the drawing of this date.

FIG 8 Drawing July 12, showing feebly the remnant of the storm to the right of and below where it first appeared

FIG 9 Photograph July 12, displaying the last vestige of the subsiding storm

This is the most remarkable midday storm ever recorded on Mars By its movement over the Martian surface and its general behavior it revealed its cloud-like nature, and gave objective proof of the existence of an atmosphere about Mars.



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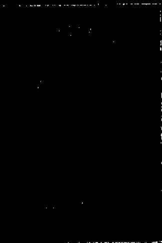

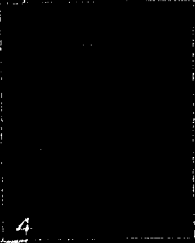

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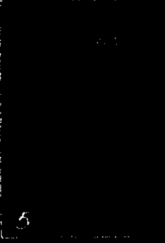

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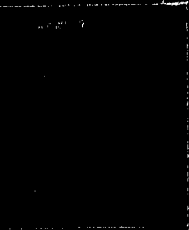

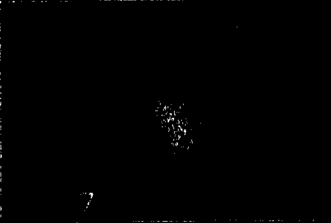

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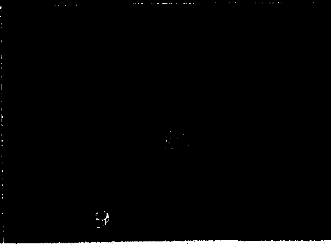


9

EXPLANATION OF PLATE VI

MARS

Direct photographs of the planet illustrating various degrees of clearness, of cloudiness, and of general opaqueness of the Martian sky in 1937

These photographs are intended to illustrate various atmospheric phenomena on Mars, such as the usual great opacity of his air to blue and violet light, and examples of blue white and of "dark clouds" Such atmospheric phenomena on a planet are best revealed by comparing photographs secured through red or yellow light filters which cut out the atmospheric haze, and photographs through blue or violet filters which obviously will register the maximum effect of a planet's atmosphere The photographs below reveal some interesting effects of the Martian air

FIGS 1, 2, 3, and 4 This group of photographs portray one of the most remarkable cases of clearing up of the *Martian air* ever observed All four photographs were taken in 1937 and are of the same face of Mars as that shown by the red light photograph in Fig 1, made on May 20 Figure 2 is a blue light photograph taken on April 20 when the Martian air was so opaque to the short wave-lengths that not enough got through to reveal any trace of the true surface markings However, in the blue photograph, Fig 3, taken May 20 his air was so transparent to these same wave-lengths of light as to reveal the actual surface markings with amazing distinctness Later, however, in June the Martian air again became opaque and no trace of the actual body of Mars is recorded in the blue light photograph in Fig 4, taken on June 24

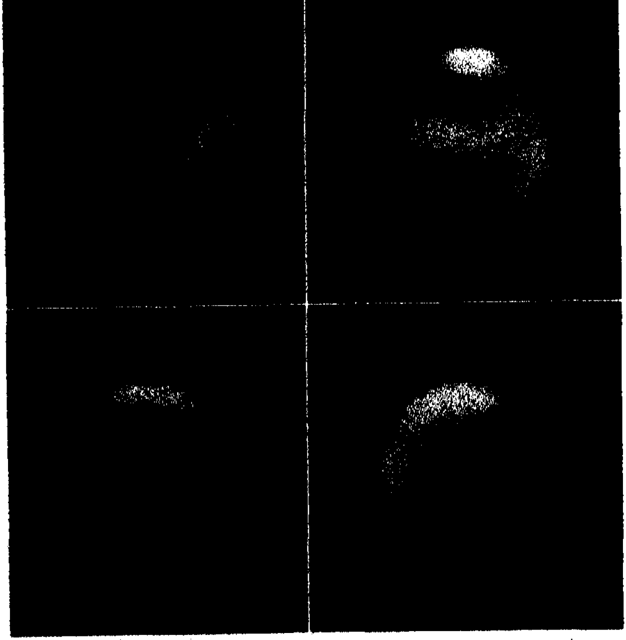
This example clearly demonstrates that the great difference between red and blue photos of Mars is produced by his atmosphere, and further evidences how great is the scattering power of the Martian air at one time and how small it may be at another Comparing the atmospheric effects in such photographs of Mars with terrestial landscape photographed likewise through different path lengths of our atmosphere at Flagstaff leads to the conclusion that the opacity of the Martian air is generally about twice that of our own atmosphere

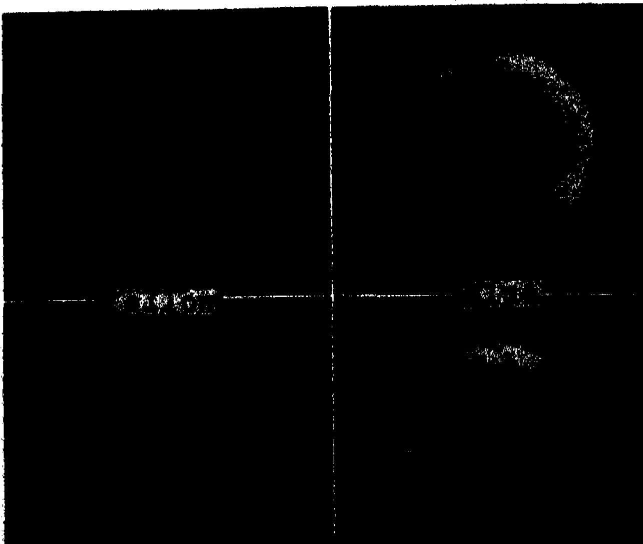
FIGS 5 and 6 Here are shown two photographs of the planet made on May 13, 1937, the one at the left through a yellow color-filter and the one at the right with blue light The blue photograph denotes by the extensive white areas over the right-hand portion of the disk that the forenoon sky of Mars was extremely hazy, while the showing through of his actual surface features toward the left side betokens that his afternoon sky was unusually clear

FIGS 7 and 8 This pair of photographs (Fig 7 in yellow and Fig 8 in blue light) taken on June 1, 1937, display the amazing effect of the Martian air in producing "dark clouds" It will be seen that the large dark areas revealed by the blue photograph do not belong to the body of the planet as the yellow image discloses, but were caused by the planet's atmosphere Photographs made on other dates before and after this one revealed the temporary character of these dark areas and indicated their atmospheric origin

Mars 1937

May 20, Red	April 20, Blue
May 20, Blue	June 24, Blue





EXPLANATION OF PLATE VII

SATURN

From 1909 to 1937

Representative photographs displaying various aspects of the ball and ring system

These views are a few examples from the photographic record of Saturn secured at the Lowell Observatory during the last 28 years, they show the planet as seen in a powerful telescope magnifying about 1,000 times, thus each image embraces an area approximately 125 times that of the Moon as seen with the naked eye

It will be noticed that the planet displays parallel belts resembling those of Jupiter These belts, like their counterpart on Jupiter, are variable as to position, form, and intensity as may be seen in the photographs

Fig 1 Photograph taken November 4, 1909, displaying the upper hemisphere as quite uniformly dark and nearly beltless Note the shadows of the ball upon the rings right side, and of the rings on the ball below

FIG 2 Photograph made February 11, 1916, which shows the upper hemisphere not as dark as in 1909, but distinctly belted It will be seen that the ball shines through Cassini's division and the outer ring evidencing how sparse the ring particles are Note the dark sash across the ball along the upper edge of the rings, which is due to its inner Crepe ring—seen against the ball

FIG 3 Photograph September 18, 1934, displays the northern hemisphere of the planet and the northern face of the rings Especially noteworthy is the strength of the dark north tropical belt here, it being the most prominent dark belt observed on Saturn since 1904, and closely resembles the strong tropical belts common to Jupiter

FIG 4. In this photograph made July 29, 1936, we see the ring system turned edgewise to us In this position the rings become extremely narrow and faint, so faint that they show only feebly in a normal photograph Against the ball of Saturn the projected rings and their shadow appear quite dark

FIGS 5 and 6 The excessive faintness of the rings in Fig 5, July 16, 1937, was due to the Earth being higher above the ring plane than was the sun, thus allowing us to see effect of one particle of the ring system shadowing the next behind it and so on, so as to cause a fainter surface of the rings than would otherwise obtain for the same tilt of the ring system Whereas in Fig. 6, October 1, 1937, the reverse is true, the sun is higher than the Earth above the rings, and all the visible surface is fully illuminated and the rings are far brighter This offers visible evidence again of the already known meteoric constitution of his rings which was proved mathematically by Maxwell and later spectroscopically revealed by Keeler

(Photograph number one by Dr Percival Lowell, the others by the author.)

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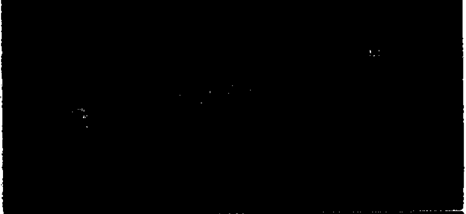

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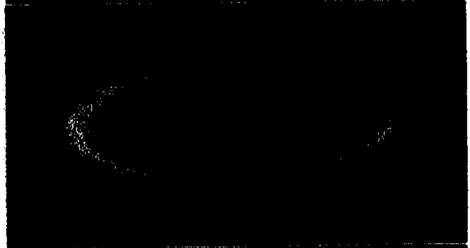

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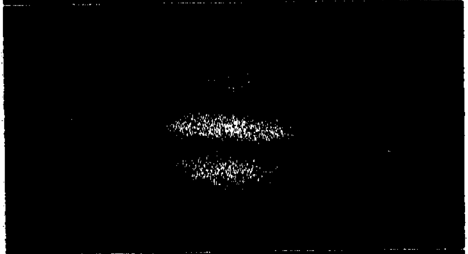

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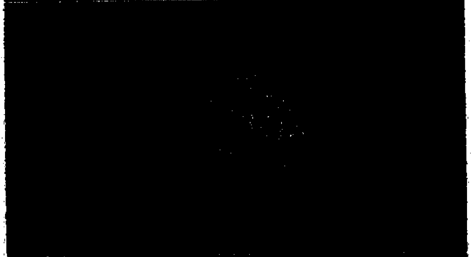

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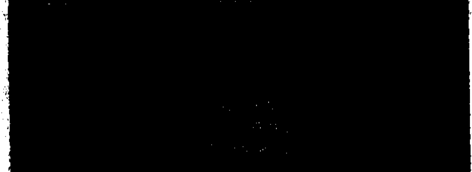
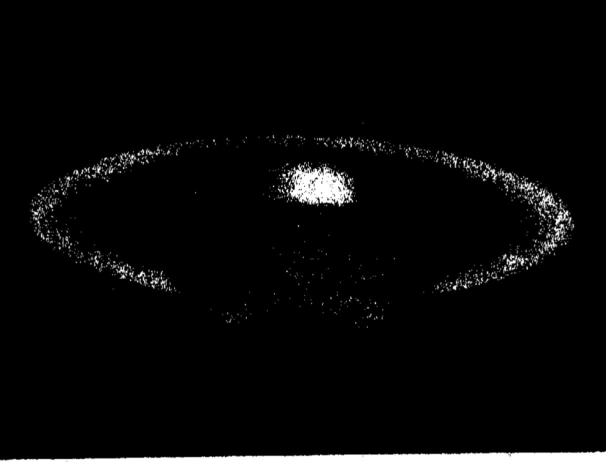
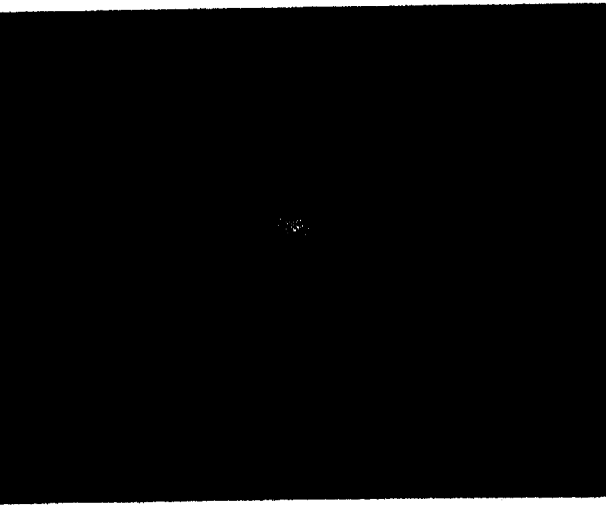


EXPLANATION OF PLATE VIII

The Great White Spot of Saturn in 1933
Drawing August 7, 1933
Photograph August 9, 1933

This outburst proved to be the most phenomenal feature recorded on Saturn in more than fifty years The spot appeared very suddenly between August 2 and 3, 1933, as an exceedingly brilliant white spot of elliptical form and about 12,000 miles long, subsequently developing in a forward direction (to the left) until by September 11 it was fully 50,000 miles long, after which it faded to invisibility by early October Meanwhile some eighteen other similar white spots, but smaller and more temporary, appeared in different longitudes in line around the planet only to subside even more quickly than did this major spot Timing the transits of the main spot and one other during 211 revolutions of the planet gave a rotation period of 10h 14m 24 2s for Saturn, agreeing closely with the period of 10h 14m 23 8s derived by Asaph Hall from a similar great white spot in December, 1876





EXPLANATION OF PLATE IX

JUPITER

September 23, 1928 October 6, 1928

The two photographs at the top illustrate the wide variety, and great complexity of detail over his surface other than the usual parallel belts

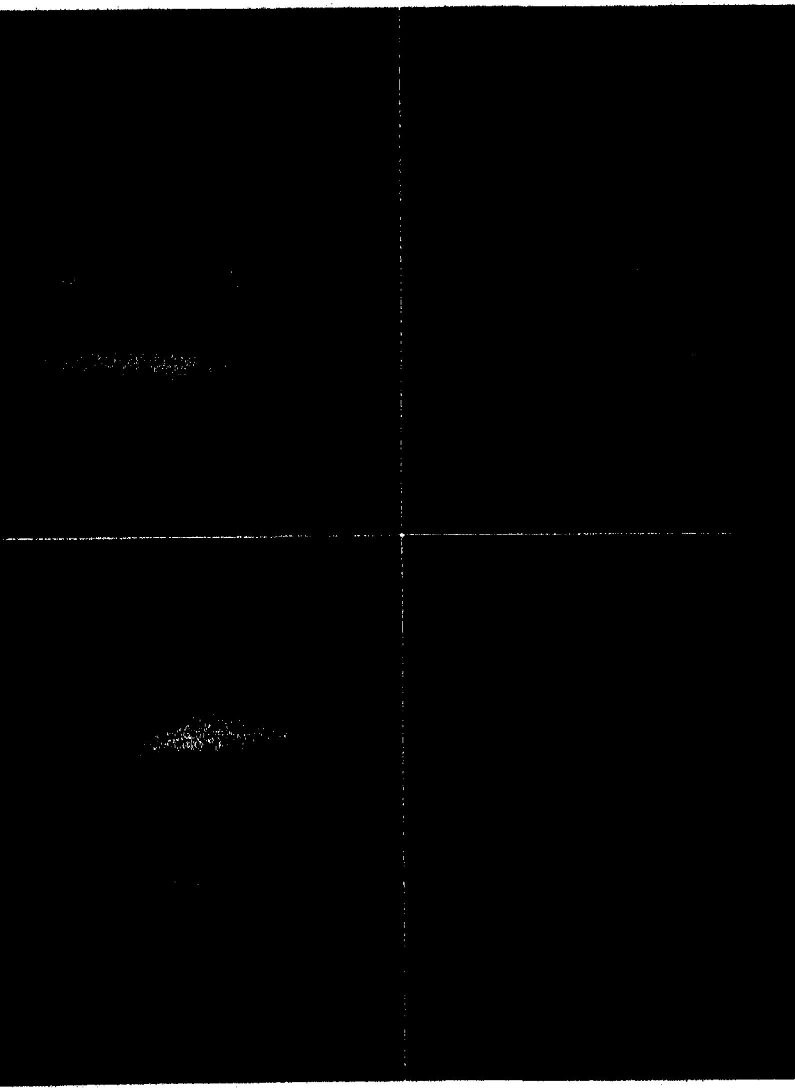
September 14, 1928 November 30, 1928

The two photographs at the bottom illustrate the rapid changes which sometimes sweep over the planet These two photographs are of the same face of the planet taken two and one-half months apart and display the great transformation of the equatorial and south tropical zones The great bright zone displayed by the left-hand photograph has become darkened in the second example by clouds of some dark material which has invaded much of the equatorial zone also The Great Red spot, the dark oval seen near the left side of the first photograph is inconspicuous amidst its dark surroundings in the second photograph The mobile character of his markings is manifested by the way spots and belts in one latitude flow past those in another latitude, those nearest the equator generally moving more rapidly than the spots in higher latitudes

Jupiter, 1928

September 23	October 6
September 14	November 30

PLATE IX



EXPLANATION OF PLATE X

JUPITER (1909–1937)

In these few examples of photographs of Jupiter, which are representative of the more than one-hundred thousand secured at Flagstaff during the last thirty years, it is intended to illustrate how the planet looked at different times, reveal some more or less typical changes, and display some interesting Jovian phenomena

FIG 1 A photograph of Jupiter with a yellow color filter taken April 27, 1909, which displays the intricate structure of the surface and at the same time evidences something of the quality of the early photographs

FIG 2 Photographs taken in the same light as Fig 1 on July 29, 1936, portraying a marked alteration in the belts

FIG 3 A photograph made September 23, 1914, which, besides displaying in great detail the precise appearance of the planet with a queer row of port-hole markings along the dark north tropical belt, records a total solar eclipse in progress there The eclipse shadow of satellite III is conspicuous to the right of the center of the disk, while, the image of the satellite itself may be faintly discerned against the sky background at the extreme left of the cut

FIG 4 This photograph made November 23, 1928, displays the planet when in a highly disturbed state as shown by the intense bright and dark markings which give a broken and disrupted appearance to the south tropical zone It is obvious here that the darkest spots are of very low albedo as compared to the brighter regions which suggests the wide diversity in the state of the material composing the visible surface

FIGS 5 and 6 These photographs taken in yellow light on February 11, 1930, and on June 10, 1936, respectively, show the oval-shaped Great Red Spot a little above and to the right of the center of the disk in both cases These comparable photographs illustrate the remarkable changes this spot, the most permanent marking on the planet, undergoes from time to time In the first example the Red Spot was very white and is here shown as the brightest part of the disk, while in the second case it was dark red and stands out as one of the darkest parts of the disk

EXPLANATION OF PLATE X A

FIGS 7, 8, and 9 This set of three photographs was taken within a few minutes of one another on June 14, 1937, in yellow, deep red, and blue light They reveal the transparent nature of the Jovian atmosphere above the belted surface, and the dominant influence of color in modifying the appearance of the planet in photographs from light of widely separated regions of the spectrum The great transparency of his atmosphere above the belts is denoted by the belts showing clear to the edge of the blue photograph The effect of color is disclosed by the difference between the red and blue photograph especially noticeable in the Red Spot where the intense redness causes it to turn dark by blue light, but nearly as bright as the rest of the disk in red light Thus, such color-filter photographs, taken practically synchronously through different color filters, exhibit rather large differences in the appearance of the markings according to the filter used because of the color reactions of the vari-colored markings themselves (i e reds photographing as bright through the red filter and as black through the blue, etc) and not by any obscuring influence of the overlying atmosphere, as some investigators have thought to be the case

JUPITER

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